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The management of communications in decentralised Bayesian data fusion system

The Management of Communications in Decentralised Bayesian Data Fusion Systems

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Forty-six thousand words

Abstract

Robert Haydn Deaves — Doctor of Philosophy
Communications Research Group — December 1998

The Management of Communications in Decentralised Bayesian Data Fusion Systems

This dissertation is concerned with the *development, evaluation and application* of a communications management algorithm in a bandwidth constrained decentralised data fusion system.

The requirement for communications management is motivated by the potential restrictions placed on the available bandwidth which arise due to a number of factors. These include hostile working environments (enemy signal jamming), low electromagnetic emission requirements (stealthy operation), large numbers of targets, and large numbers of platforms.

This dissertation documents the *development* of an information theoretic approach to the decision problem of communications management. The thesis is based on two propositions concerned with the scientific *evaluation* and engineering *application* of communications management. Seven hypotheses are stated which are counter to the propositions. These hypotheses are *tested* experimentally to lend support and maintain the *evaluation* and *application* propositions.

The dissertation makes three major contributions to the scientific body of knowledge of the data fusion community:

1. The *development* of the first information based algorithm to manage a limited communications bandwidth in a decentralised, multi-platform, multi-target, battlespace tracking and identification simulator. This work employs, and builds on, that carried out by other researchers.
2. The *evaluation* of an information based approach to communications management. Here the information based approach is compared with an ad-hoc algorithm, i.e. a round-robin algorithm. The comparison indicates that the information based approach out-performs the round-robin algorithm.
3. The *application* of communications management to the problem of avionic system design. The results indicate that the performance of different avionic resources, i.e. processors, sensors, and numbers of platforms, can be traded individually or collectively with the communication resource. A simple hypothetical paper based avionic design example is provided that demonstrates this *trade-off potential.*

The dissertation concludes that the thesis *evaluation* and *application* propositions have been maintained. A critique of the research and future work are documented.

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I would like to acknowledge a number of individuals and institutions for their encouragement and support for the work documented in this thesis:

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Last, but by no means least, I would like to thank my wife, Elaine, and twin daughters, Rhiannon and Megan, for their love and support and for showing me what is really important in life.

Author's Declaration

I declare that the work in this dissertation was carried out in accordance with the Regulations of the University of Bristol. The work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree.

Any views expressed in the dissertation are those of the author and in no way represent those of the University of Bristol or British Aerospace.

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

SIGNED: R. H. Deaves DATE: 21st April 1999

Robert Haydn Deaves December 1998

BRITISH AEROSPACE
Sowerby Research Centre

UNIVERSITY OF BRISTOL
Department of Electrical and Electronic Engineering

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Nomenclature

Ⓢ	-	sensor
Ⓝ	-	decentralised processing node
$\rightarrow$	-	one way communication link
$\leftrightarrow$	-	two way communication link
N'	-	broadcast communication node
N''	-	non-fully connected decentralised node
$I(1) - I(3)$	-	information for communication
$P(\mathbf{X}, \mathbf{Z})$	-	probability of $\mathbf{X}$ and $\mathbf{Z}$
$P(\mathbf{Z}, \mathbf{X})$	-	probability of $\mathbf{Z}$ and $\mathbf{X}$
$P(\mathbf{X} \vert \mathbf{Z})$	-	probability of $\mathbf{X}$ given $\mathbf{Z}$
$P(\mathbf{Z} \vert \mathbf{X})$	-	probability of $\mathbf{Z}$ given $\mathbf{X}$
$P(\mathbf{X})$	-	probability of discrete states $\mathbf{X}$
$P(\mathbf{Z})$	-	probability of $\mathbf{Z}$
$\forall$	-	predicate logic operator *for all*
$\mathbf{Z}^k$	-	set of k observations
$\mathbf{Z}^{k-1}$	-	set of $k-1$ observations
$Z(k)$	-	the k^{th} observation
ΔT	-	time between two consequative updates
$\mathbf{x}(k)$	-	true continuous state at index k
$\mathbf{F}(k)$	-	state transition matrix at index k
$\mathbf{w}(k)$	-	state noise at index k
$\mathbf{z}(k)$	-	observation state at index k
$\mathbf{H}(k)$	-	observation matrix at index k
$\mathbf{u}(k)$	-	observation noise at index k
$\mathbf{R}(k)$	-	observation noise matrix at index k
$\tilde{}$	-	estimate
$\hat{}$	-	prediction
$\vert\vert$	-	determinant operator

$E[\cdot]$	-	expectation
$\tilde{\mathbf{P}}(k\|k)$	-	estimate covariance at time index k
$\hat{\mathbf{P}}(k\|k-1)$	-	prediction covariance at index k using the information available at index $k-1$
$\tilde{\mathbf{x}}(k\|k)$	-	state estimate at time index k
$\hat{\mathbf{x}}(k\|k-1)$	-	state prediction at index k using the information available at index $k-1$
$\mathbf{Q}(k)$	-	process noise covariance
l	-	dimension of the state
$\mathbf{y}(\cdot)$	-	state information vector
$\mathbf{Y}(\cdot)$	-	state information matrix
$\mathbf{i}(\cdot)$	-	observation information vector
$\mathbf{I}(\cdot)$	-	observation information matrix
$v(k)$	-	Kalman filter innovation
$\mathbf{S}(k)$	-	Kalman filter innovation covariance
$\mathbf{W}(k)$	-	Kalman filter gain matrix
$P(\mathbf{X}\|\mathbf{Z}^k)$	-	identification probabilities for target types $\mathbf{X}$ given the observation set $\mathbf{Z}^k$
$\mathcal{Y}$	-	posterior logarithmic identification information
$\mathcal{I}$	-	observation logarithmic identification information
L_f	-	number of communication links in a fully connected decentralised system
L_f	-	number of communication links in a non-fully connected decentralised system
$\mathbf{m}(k)$	-	Partial state information vector for communication
$\mathbf{M}(k)$	-	Partial state information matrix for communication
$\mathcal{M}(k)$	-	Partial identification information vector for communication
$\mathbf{J}(k)$	-	Fisher information
$p(\mathbf{x})$	-	continuous distribution of the state $\mathbf{x}$
I_e	-	discrete elemental information
I_v	-	discrete vector information
$H(\cdot), h(\cdot)$	-	entropic information
$I_{am}^{XX}(k)$	-	absolute information distance for track $(XX = Tr)$ and identification $(XX = Id)$ at index k
$I_{rm}^{XX}(k)$	-	relative information distance for track $(XX = Tr)$ and identification $(XX = Id)$ at index k
$U(\cdot)$	-	utility function

$d1 \ldots d4$	-	decision routes
$I1 \ldots I4$	-	information states
θ	-	information state when $\mathbf{X}$ and $\mathbf{x}$ are combined
τ	-	time delay
σ	-	standard deviation
r_g	-	platform to target distance
n_t	-	percentage accuracy of communications management decision values
r	-	reduction in decision values
$f(\cdot)$	-	performance function
P_d	-	probability of detection
P_c	-	probability of communication
a_v	-	maximum acceleration
n_t	-	percentage noise on decision values
i, j, k, t, c, m, n	-	various indicies
K, T, N, M	-	maximum number of observations, targets, platforms and Monte Carlo simulations respectively

Abbreviations

SRC	-	The Sowerby Research Centre
BAe	-	British Aerospace PLC
MIT	-	Massachusetts Institute of Technology
USA	-	United States of America
OxNav	-	Oxford University Navigation Vehicle
RAF	-	Royal Air Force (United Kingdom)
USAF	-	United States of America Air Force
CCD	-	Charge Coupled Device
JTIDS	-	Joint Tactical Information Distribution System
JDL-DFS	-	Joint Director of Laboratories Data Fusion Sub-Panel (USA)
DoD	-	Department of Defence (USA)
DKF	-	Decentralised Kalman Filter
EMC	-	Electromagnetic Compatability
AWACS	-	Airborne Warning and Control System
ESA	-	Electronically Scanned Array radar
DFTB	-	Data Fusion Test Bed (SRC)
ESPRIT	-	European Science Programme for Research in Information Technology
SKIDS	-	Signal Knowledge Integration with Decisional Control for Multi-Sensory Systems
LISA	-	Locally Intelligent Sensor Agent
LICA	-	Locally Intelligent Control Agent
DRA	-	Defence Research Agency (UK)
DERA	-	Defence Evaluation Research Agency (UK)
DAF	-	Distribution Approximation Filter
SLOP	-	Support LOgic Pair

EKF	-	Extended Kalman Filter
C^3I	-	Command, Control, Communication and Intelligence
GMU	-	George Mason University (USA)
IEEE	-	Institution of Electrical and Electronic Engineering (USA)
SMC	-	IEEE Journal on Systems, Man and Cybernetics
SPIE	-	Society of Photo-Optical Instrumentation Engineers
NATO	-	North Atlantic Treaty Organisation
RTO	-	Research Technology Organisation (NATO)
AGARD	-	Advisory Group for Aerospace Research and Development (NATO)
IEE	-	Institution of Electrical Engineering (UK)
WWW	-	World Wide Web
AI	-	Artificial Intelligence
TDMA	-	Time Division Multiple Access
IFF	-	Identify Friend of Foe
MOE	-	Measures of Effectiveness
HMI	-	Human Machine Interface
ALFAS	-	Affordability, Lethality, Flexibility, Availability and Survivability

Notes for Reading the Dissertation

This section provides some useful notes for those reading the dissertation:

words in italics	-	Emphasised words or phrases.
'words in single quotes'	-	Higher emphasis on words or phrases.
words in bold	-	Highest emphasis on words or phrases.
thin boxed words	-	Important point(s) relating to the thesis.
medium boxed words	-	A hypothesis related to a thesis proposition.
thick boxed words	-	A proposition related to the thesis.

Definitions Used in the Dissertation

This section provides some useful definitions used in the dissertation (McLeod 1987) (Borowski and Borwein 1989).

Additional definitions are provided in the body of the dissertation as appropriate. Those listed below provide a useful common platform to start reading the dissertation.

target	-	Anything that is fired at or made an objective of warlike operations. In the context of this thesis these are potentially hostile aircraft.
sensor	-	Device giving signal for detection or measurement of a physical property to which it responds. In the context of this thesis the sensor provides a measurement, represented as data, concerning the *identity* and *location* of a target.
data fusion	-	Combining diverse and uncertain sensor measurements and other sources of information with the aim of making an estimate or inference. (Manyika and Durrant-Whyte 1994).
sensing node	-	The coupling of a sensor, appropriate processor and data fusion algorithm into a single node.
sensing platform	-	A collection of sensing nodes co-located or a number of sensors with appropriate processor(s) and data fusion algorithms, typically on a discrete 'platform' such as an aircraft.

sensing system	-	A collection of sensing platforms, generally with some interaction.
management	-	The control of 'activities' through decision. In the context of this thesis these activities correspond to inter-platform communications.
communication	-	The act of transmitting and receiving data through a transmission medium.
bandwidth	-	A measure of data transfer through a communication link.
information	-	A mathematical abstraction of the content of any meaningful statement or data, enabling the study of the most efficient way of recording or transmitting them.
entropy	-	A measure of disorder.
decentralised	-	No single (central) point of control, i.e. decisions on resource allocation and utilisation are made locally throughout the system, but the system on the whole behaves as if there was a central controller.

Dissertation Overview

Figure P.1 (page xxvi) represents the road map for the dissertation. This comprises nine chapters. Each chapter is provided with an introduction and summary/concluding remarks sections that inform the reader of the aims of the chapter and how these have been achieved respectively. Arrowed lines are used to show the reader the connection between different chapters with dotted lines showing 'weak' connections. In addition to the chapters, research requirements and capabilities, and new research are also highlighted. Further, the location of thesis proposition statements, hypotheses generation and testing are also represented on Figure P.1.

A broad outline of the dissertation areas, i.e. 'what and why?', 'how?', 'results and analysis' and 'contribution', are provided on the right hand side of the diagram. These areas are expanded below:

What and why?

This section of the dissertation aims to answer the broad question 'what are the subject areas employed in the thesis and why are they being employed?' This question is answered in the first four chapters of the dissertation:

- **Chapter 1: Introduction**
  The aim of this chapter is to provide an introduction to the dissertation. This is achieved by stating the thesis and its associated propositions and providing brief introductions to the main dissertation sections, i.e. 'what and why?', 'how?', 'results and analysis' and 'contribution'.

- **Chapter 2: Decentralised Data Fusion Systems**
  The aim of this chapter is to identify the subject areas of the thesis and provide support for their use. The areas covered include decentralised systems, communications management and system design. These subject areas are used to justify and define the *thesis requirements.* In addition, Bayesian data fusion algorithms and informa-

tion based decision theory are introduced. These are considered further in Chapters 3 and 4 respectively.

- **Chapter 3: Bayesian Data Fusion Algorithms**
  This chapter aims to identify and justify the Bayesian data fusion algorithms employed in the thesis. Here two estimators are considered, one based on a target's kinematics the other on its identity. Further, the application of these algorithms to decentralised systems are discussed. These subject areas are used to define the *infrastructure capabilities* required for the thesis.

- **Chapter 4: Information Based Decision Theory**
  Here the information metrics and decision techniques used in the thesis are identified and justified. These subject areas include entropic information, update data, absolute information gain, utility theory and decisional trees. Further, these subjects provide the *management capabilities* for the thesis.

How?

This section of the dissertation aims to answer the broad question 'how will communications management be implemented, evaluated, applied and tested in the context of this thesis?'

- **Chapter 5: Communications Management in Decentralised Systems**
  This chapter of the dissertation takes the knowledge documented in Chapters 1 to 4 and applies and develops it to answer the question 'how will communications management be implemented, evaluated and applied in the context of this thesis?' This involves the documentation of the information based communications management algorithm employed in the thesis. Further, this chapter generates a number of hypotheses related to the *evaluation* and *application* propositions, i.e. **Propositions 1 and 2**. These hypotheses are to be *tested* in Chapters 7 and 8 in order to lend support to the thesis propositions. In addition, this chapter generates the *test-bed capability* of the thesis.

- **Chapter 6: Decentralised Multi-Platform Multi-Target Simulator**
  This chapter aims to apply the test bed capability to develop a simulator for testing the evaluation and application hypotheses. Here the design and implementation details of a multi-platform and multi-target battlespace tracking and identification simulator are provided. Further, the scenarios used to test the evaluation and application hypotheses are documented. These test scenarios, along with the hypotheses

definitions of Chapter 5, lead to the evaluation and application of communications management in Chapter 7 and 8 respectively.

Results and Analysis

The results and analysis of the investigations are documented in Chapters 7 and 8. Further, discussion on the research results are also included:

- **Chapter 7: An Evaluation of Communications Management**
  This chapter documents the results, analysis and discussion of the investigations into the evaluation of the decentralised communications management. This is achieved through a comparison of an information based algorithm with an ad-hoc, i.e. round-robin, approach. Here the evaluation hypotheses are *tested* which lends support to the evaluation proposition, i.e., **Proposition 1**. The additional knowledge gained from this investigation is documented as 'rules of thumb'.

- **Chapter 8: Towards The Design of Decentralised Systems**
  Here the results, analysis and discussion of the investigations into the application of the decentralised communications management are documented. This is achieved through investigating the trade-off potential between the resources of an avionic sensing system, i.e., processors, sensors and number of platforms, and a managed communications resource. The trade-off potential are first considered on a *pair-wise* basis and then collectively. Here support is provided for the application proposition, i.e., **Proposition 2**, by *testing* the application hypotheses. 'Rules of thumb' are generated to document additional knowledge gained from the investigations.

Contribution

This is documented in a single chapter along with the thesis conclusions and future work:

- **Chapter 9: Conclusions and Future Work**
  The primary aim of this chapter is to emphasise the contribution of the dissertation to the scientific body of knowledge of the data fusion community. This is achieved by stating the contribution in three primary areas: the *development*, *evaluation* and *application* of communications management in a decentralised battlespace sensing system. Further, a critique of the work is provided which leads to a discussion on future work in the general area of data fusion and more specifically communications management. In addition, a brief discussion on how the knowledge gained could be applied to other areas is provided.

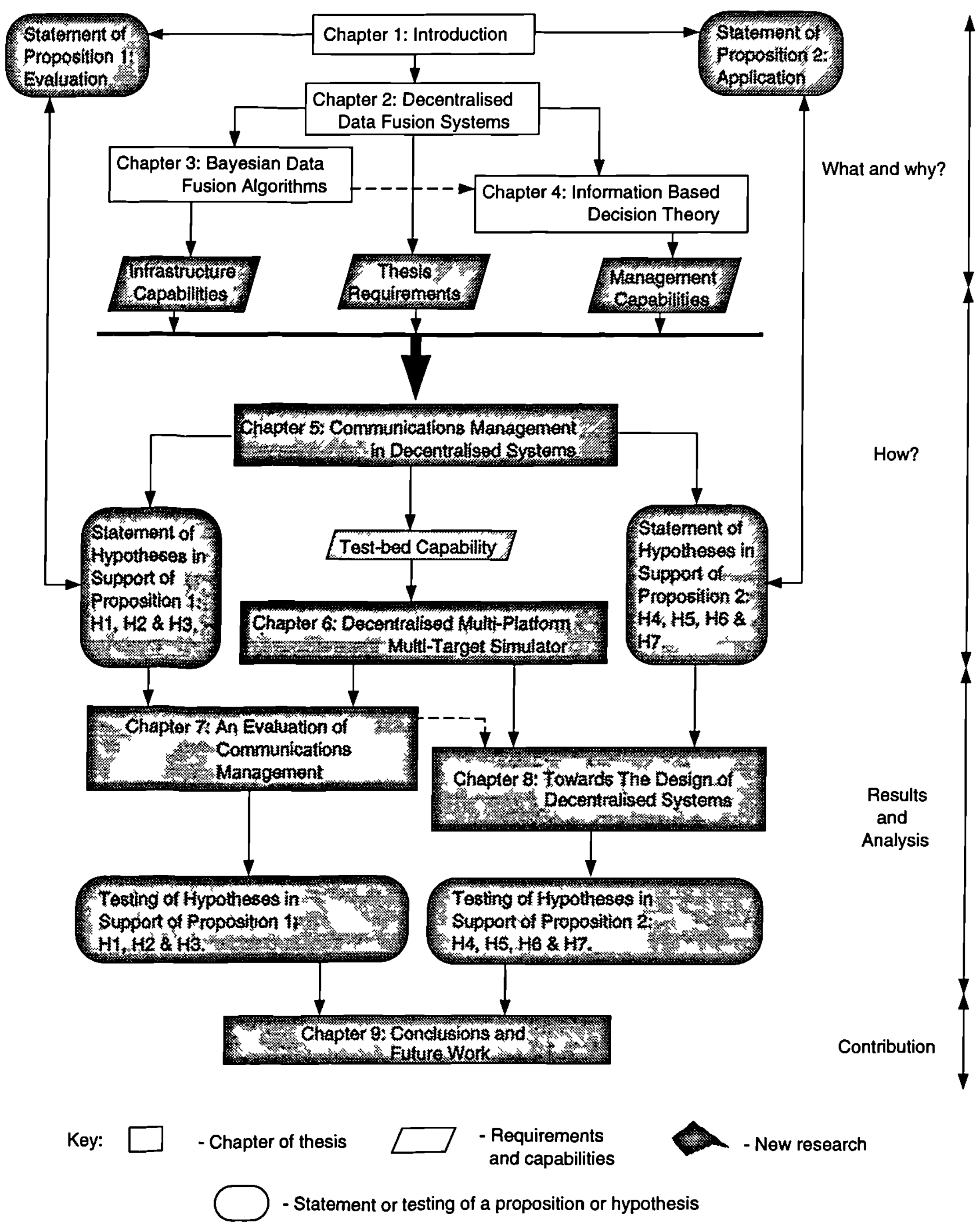


Figure P.1: Dissertation 'road-map'.

Chapter 1

Introduction

<table><tr><td>
This dissertation describes the development, evaluation and application of an information based communications management algorithm in a bandwidth constrained decentralised sensing system.
The thesis is that: an information based approach to communications management in a decentralised sensing system (i) can out-perform non-information based methods, and (ii) can provide a trade-off potential with other system resources.
It is stated as two propositions:
Proposition 1: <u>Evaluation of Communications Management.</u>
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides a measurable increase in performance when compared with ad-hoc approaches.'
Proposition 2: <u>Application of Communications Management.</u>
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides the potential for trade-offs to be made/evaluated/calculated between the performance of the communications system and other resources.'
</td></tr></table>

The purpose of this chapter is to provide an overview of the main technical themes of this thesis (the 'what'), and the motivations for them (the 'why'). The approach adopted for investigating the thesis (the 'how') and associated results and scientific contribution are also presented.

This chapter is organised as follows, see Figure 1.1: Section 1.1 introduces the central technical themes of the thesis. Section 1.2 discusses *why* communications management has been chosen as the subject matter of the thesis. Section 1.3 discusses *how* the thesis investigations will be carried-out. Details of the results and analysis methods are provided in Section 1.4. This includes the constraints and contribution of the thesis. This chapter concludes with a summary in Section 1.5.

1.1 What are the main technical themes?

This question is answered by providing a progressive introduction to the main technology areas of the thesis. These include sensing systems and data fusion, centralised and decentralised systems, and communications issues.

1.1.1 Sensing Systems and Data Fusion

Sensing systems play an integral part of every day life in the latter part of the 20th century. Examples of such sensing systems include: bar code readers in supermarkets, detectors used in traffic light systems and temperature detectors in automatic washing machines. Further, their use in less frequently encountered areas is also significant. These systems include: medical scanning equipment, robotic and automation applications, and satellite localisation systems. All these examples aim to improve the quality of our lives in numerous ways, including health, transportation, convenience, cost, and environmental preservation (Luo and Kay 1992).

The influence of such sensing systems will undoubtedly increase to meet society's requirements as we enter the new millennium. Developments in signal processing theory, techniques and applications, and evolving sensor technologies coupled with processors that are ever more powerful provide the tools for realising these needs. Maximising the utilisation of such **sensing systems** has lead to the development of a technological area referred to as *data fusion.*

In full generality, data fusion can be defined as the process of *combining diverse and uncertain sensor measurements and other sources of information with the aim of making an estimate or inference concerning the state of nature* (Manyika and Durrant-Whyte 1994). It involves aspects of system architecture, signal processing, and resource management.

1.1.2 Centralised and Decentralised Systems Architectures

Systems consisting of several sensors, i.e. *multi-sensor* systems, may be connected together in a number of ways. This has been the focus of a large research effort from the defence industry (Waltz and Llinas 1991). To date, the most popular connectivity has been a *centralised* architecture. Here, each sensor communicates all its data to a central processing node where the *estimated state* is calculated.

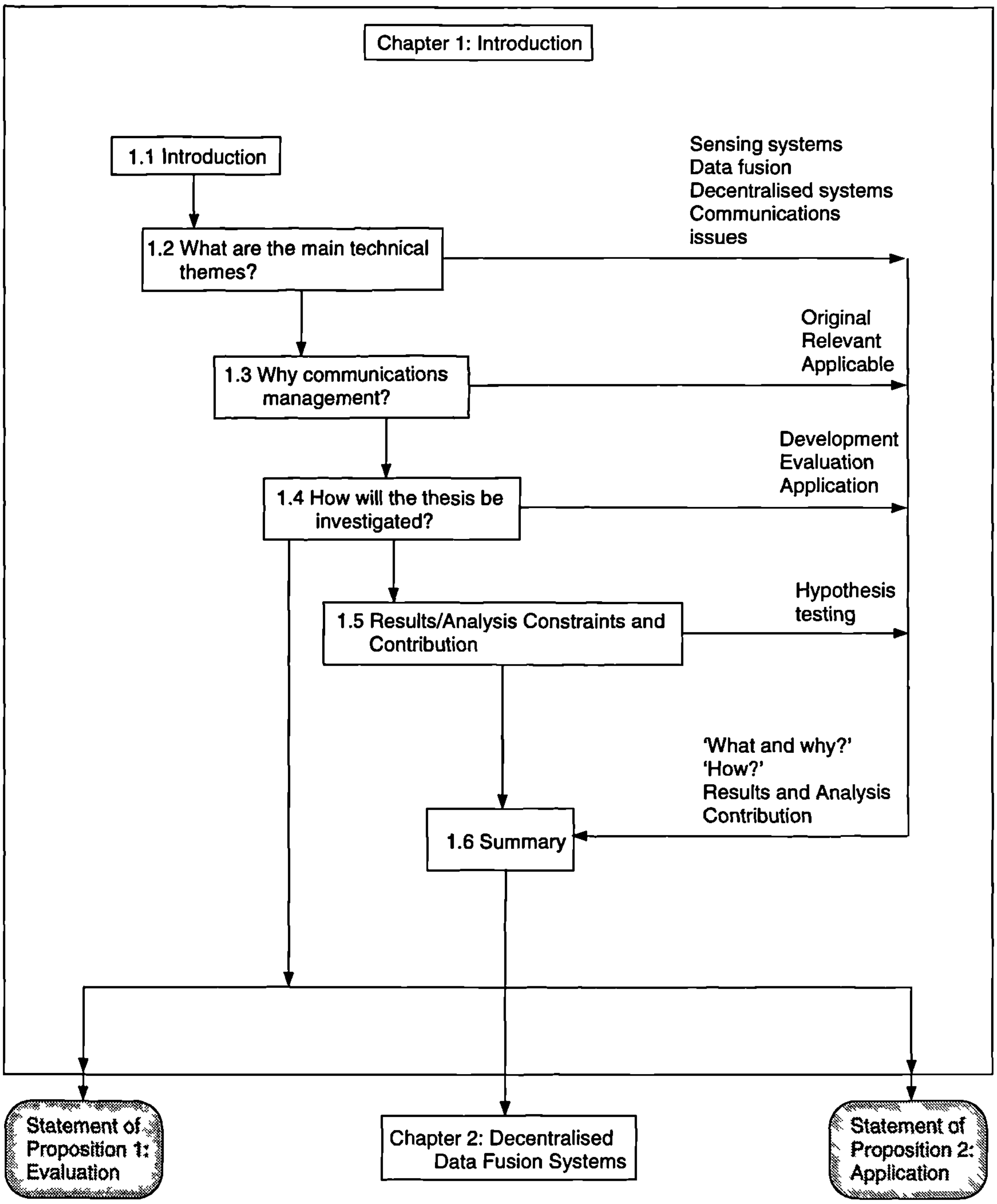


Figure 1.1: Reader's map for Chapter 1.

Other configurations include a range of *decentralised* systems. These systems employ processing units co-located with each sensor. However, such systems do not employ a central processing facility. Instead each processing unit communicates some or all of its *local estimated state* to some or all of the other processing units. Further, each processing unit is then able to calculate (an approximation to) the overall *estimated state*.

Decentralised systems offer a number of advantages over centralised systems. These include modularity, flexibility, scalability and survivability. Such advantages warrant a research effort in the general area of decentralised architectures for multi-sensor data fusion systems.

1.1.3 Communications Issues

One important area that requires research is the effect that constrained communications bandwidth between the processing nodes of a decentralised system has on its performance. By constrained we mean a bandwidth unsufficient to communicate either all the data available at any time, or to all possible recipients. Further, ways of utilising or managing this valuable communications bandwidth resource has, to date, received little research effort. This is referred to as **communication management**.

A communications channel in a decentralised system can become constrained due to a number of reasons. These include hostile working environments, low electromagnetic emission requirements, large number of targets, and large numbers of processing nodes.

The work presented in the thesis develops that previously carried out for resource management in decentralised systems. That work employed **entropic information** metrics as a basis for decision making in sensor management. Here similar entropic information metrics are applied to the management of a constrained communication channel. An information based approach to resource management, including communications, has a number of advantages (Manyika and Durrant-Whyte 1994). These include:

1. The sensing systems investigated in this thesis are concerned with target tracking and identification. These target characteristics can be represented by scalar information values (Hintz and McVey 1991). This makes information suitable for decision making.

2. The approach has been applied to other areas of decentralised systems including sensor management (Manyika and Durrant-Whyte 1994), system organisation (Ho 1994), and network management (Utete 1994). As such, a similar approach applied to communications management has the desirable potential of compatibility.

3. The approach is being investigated for application in the area of general system design (Noonan 1995). Again, a similar approach applied to communications management has the desirable potential of compatibility.

This section has answered the question 'what are the main technical themes?' (relevant to the thesis). This has been achieved by providing introductory details on sensing systems and data fusion, centralised and decentralised systems, and communications issues. These areas are discussed further in Chapter 2. This leads to the *central theme* of the thesis, i.e. **information based communications management in decentralised sensing systems.**

1.2 Why communications management?

This question is best answered in terms of previous work by considering communications management, its use in battlespace scenarios, and its engineering application.

1.2.1 Previous Work

A literature review of public domain conference and journal papers indicates that only a few researchers appear to be investigating the effects of reduced communications bandwidth in sensing systems. Further, most of this work has been carried-out during the past few years. The majority has been focussed on reducing the resolution of the data so that it *fits* the available communications bandwidth (Olivier et al. 1995) (Black and Bedworth 1998) (Wong et al. 1998).

An exception to this approach is presented in (Alford et al. 1996). Here the *effects* of reducing the communications bandwidth of a distributed tracking system are presented. Performance values for targets with different process and sensor noise values are provided. These are related to different communications bandwidths. It should be noted that this paper did not offer a *management* scheme to this problem. This was still true in their more recent publication (Chang et al. 1998).

In decentralised systems no work has been carried-out on managing a decentralised communications resource. Related work on decentralised algorithms (Rao et al. 1993), non-fully connected topologies (Grime 1993) and information based sensor management (Manyika and Durrant-Whyte 1994) has been carried-out. These can be applied and developed to realise information based communications management.

Therefore, the work presented in this thesis on the **development** of a communications management algorithm is *novel* since only a few researchers have recently started investigating the area for centralised and distributed systems. Further, the research is *original* (and being investigated for the first time) since (i) an information based approach to communications management in sensing systems is being evaluated, and (ii) it is being applied in decentralised systems.

1.2.2 Battlespace Scenarios

This section of the thesis outlines a battlespace trial concerned with fighter aircraft communicating sensed data. This example adds weight to the motivation for communications management.

The potential performance benefit of platforms communicating data was reported in 'The Mail on Sunday', June 30th, 1996. This article reported the annual air exercise between the RAF and USAF. Here the RAF had implemented the inter-aircraft communication system, JTIDS (Joint Tactical Information Distribution System) (Toone 1978). This allowed, for the first time, the RAF F3 Tornados (see Figure 1.2) to out fly the Americans with a four-to-one 'kill' ratio. Further, this was achieved with no 'fratricides'.

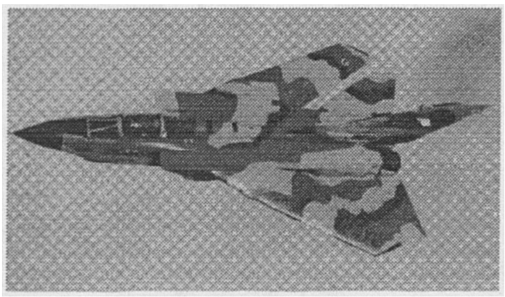


Figure 1.2: British Aerospace Tornado fighter aircraft.

The article provided no details of the enemy jamming capabilities employed during the trial. It is *assumed* that if the inter-aircraft bandwidth was reduced the RAF system performance would reduce, i.e. a reduction in the kill ratio would be experienced. Further, it is posited that if an *information based management scheme* was used to control data flow through the reduced bandwidth link, an improvement in system performance, when compared with a non-information based algorithm can be achieved.

Such battlespace trials increase the relevance of the investigations into communications management as the knowledge gained has application to current and future systems. Further, investigations are required to prove the 'assumptions' relating to communications management. This will be achieved through the **evaluation** of communications management.

1.2.3 Engineering Application

This section highlights an engineering application area in which the results of communications management investigations may be applied. This is based on system design.

British Aerospace (BAe), as one of the World leaders in the aerospace industry, is committed to engineering excellence through-out the life-cycle of its products (BAe 1998). In order to fulfill this commitment BAe is carrying out research in a number of 'leading edge' systems related areas including decentralised systems. This thesis contributes to this research area by **applying** results obtained from investigating communications management to that of decentralised system design.

> The question 'why communications management?' has been answered by providing literature review details that indicate that the **development** of a communications management algorithm for decentralised systems provides original research. Further, the relevance of the work is emphasised through providing details of a battlespace trial held between the RAF and USAF. Here assumptions relating to the benefit of communications management have to be tested through **evaluation**. In addition, the knowledge gained may have relevance to the engineering **application** area of system design.

1.3 How will the thesis be investigated?

The work reported in this dissertation comprises three investigation areas, concerned with the development, evaluation and application of communications management respectively.

1.3.1 Communications Management Development

This investigation is concerned with applying work carried-out by other researchers in the broad areas of 'Decentralised Data Fusion Systems', 'Decentralised Bayesian Data Fusion Algorithms' and 'Information Based Decision Theory' to provide the *thesis requirements*, *infrastructure capabilities* and *management capabilities* respectively. These are investigated further in Chapters 2, 3 and 4.

These requirements and capabilities are **developed** so that 'Communications Management in Decentralised Systems' can be investigated. This is documented in Chapter 5. This provides a *test-bed capability* that is realised by the 'Decentralised Multi-Platform Multi-Target Simulator' documented in Chapter 6. This comprises two major estimation sub-systems, one based on a target's identification, the other based on a target's track.

1.3.2 Communications Management Evaluation

This area is concerned with the evaluation of communications management in decentralised battlespace sensing systems. Here an information theoretic approach to communications management is compared with a non-information based algorithm. The purpose of this evaluation is stated in the following proposition:

Proposition 1: Evaluation of Communications Management.
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides a measurable increase in performance when compared with ad-hoc *approaches.*'

Further, three hypotheses related to Proposition 1 will be stated. These are concerned with system performance when the communications management is (i) based on track or identification information only, (ii) based on track and *identification information in* combination, and (iii) operates in scenarios where the targets are very similar.

The investigations aim to test these hypotheses in order to lend support to Proposition 1.

1.3.3 Communications Management Application

This research is concerned with the application of the results and knowledge generated from the preceding investigations to a system design exercise. Here the trade-off potential between different components of an avionic system are compared individually and in combination with the communication system performance. This application requirement is stated in the following proposition:

Proposition 2: Application of Communications Management.
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides the potential for trade-offs to be made/evaluated/calculated between the performance of the communications system and other resources.'

Four hypotheses related to Proposition 2 will be stated. Three are concerned with the trade-off potential between the communication system performance and (iv) processor, (v) sensor and (vi) number of platforms. The final hypothesis is concerned with trade-off potential between the (vii) processor, sensor, number of platforms and communication system in combination.

The investigation aims to test these hypotheses in order to lend support to Proposition 2.

The question 'how will the thesis be investigated?' was answered by considering three areas: (i) **development**, (ii) **evaluation**, and (iii) **application** of communications management. The **thesis** is based on two propositions concerning the **evaluation** and **application** of communications management. Seven hypotheses related to the propositions are introduced. This research aims to *test* these hypotheses in order to lend support to the propositions and maintain the thesis.

1.4 Results/Analysis, Constraints and Contribution

In this section an overview is provided of the results/analysis, constraints and scientific contribution of the thesis.

1.4.1 Results/Analysis

The results of the investigations are represented as *process models.* These relate the system performance metrics to the managed inter-platform communications bandwidth. These process models can then be analysed in order to test the hypotheses and lend support to the *evaluation* and *application* propositions. This ensures the thesis is maintained.

In addition, other knowledge generated from the investigations will be documented. These may take the form of 'rules of thumb' that can be used to predict how to achieve certain system performance, e.g. 'increasing the sensor performance improves system performance more than increasing the communications bandwidth'.

1.4.2 Constraints

The following constraints are placed on the investigations of the thesis:

1. **Simple data fusion algorithms:** The thesis is not concerned with the state-of-the-art tracking and identification algorithms. Here simple algorithms are employed, i.e. a *linear* information-filter kinematic estimation algorithm, a simple data association algorithm, and a basic recursive identification estimation algorithm. These allow the effects of communications management to be clearly analysed without the influences of effects associated with more advanced trackers, e.g. JPDAF (Bar-Shalom 1992a).

2. **Simulation based approach:** The thesis employs a simulation to carry-out the investigations. Although the use of real military systems would have been preferred, it was unfortunately not a practical option for this work.

3. **Simplistic performance metrics:** The thesis employs simple metrics to gauge the performance of the communications management algorithm. These are based on the average determinant of track covariance or average identification time to reach some identification probability.

Implementation constraints are described and discussed in the relevant chapters.

1.4.3 Anticipated Contribution of the Dissertation

The thesis makes three major contributions to the body of knowledge of data fusion:

1. **Communication Management Development:** This research involves reviewing the work of others and applying and developing the technologies to deal with bandwidth constraint in decentralised sensing systems. This will result in the implementation of the *first* communications management algorithm for a decentralised battlespace sensing system.

2. **Communications Management Evaluation:** This research involves the statement and testing of the evaluation related hypotheses. These will then lend support to **Proposition 1**, i.e. an information theoretic approach to communications management provides better performance than an ad-hoc approach. Other knowledge gained from the investigations will be documented.

3. **Communications Management Application:** This research involves the statement and testing of the application related hypotheses. These will then lend support to **Proposition 2**, i.e. the knowledge gained about communications management can usefully be applied to system design. Other knowledge gained from the investigations will be documented.

This section of the thesis has provided details of the results/analysis methods, constraints of the research, and anticipated contribution. Primarily, the results and analysis are concerned with the testing of the hypotheses. This is achieved under the constraints of simple data fusion algorithms in simulation. **The major contribution of the research is in the development, evaluation and application of a novel and high performance communications management algorithm for decentralised sensing systems.**

1.5 Summary

This chapter of the thesis has introduced the main dissertation sections.

- *What and why?*
  In these sections of the chapter the subject areas of the thesis were introduced and justified. These include sensing systems, data fusion, decentralised systems and communications issues. Further, the subject area of an information based approach to communications management in decentralised systems is identified as an original, relevant and applicable research topic. As such, it is deemed a suitable research area for this thesis.

- *How?*
  This section of the chapter provides an introduction as to how the research is carried-out. This is based on three major areas: (i) the development, (ii) evaluation, and (iii) application of communications management in decentralised systems. The thesis of the dissertation is based on two propositions based on the evaluation and application of communications management. Further, seven hypotheses are stated which are related to the propositions.

- *Results and Analysis*
  Here details of the thesis results and analysis are provided. The results are presented as process models which relate the system performance metrics to the inter-platform communications bandwidth. These are then employed to *test* the hypotheses which lend support to the thesis propositions.

- *Contribution*
  The primary aim of this section is to emphasise the contribution of the dissertation to the body of knowledge of the data fusion community. If the development of the information based communications management algorithm is successful it will provide the *first* implementation of such an algorithm to decentralised systems. Further, by testing the thesis hypotheses the evaluation and application propositions are maintained lending support for the thesis that (i) 'an information based approach to communications management out-performs non-information based algorithms' and (ii) 'the results of the investigations can be applied to decentralised system design'.

Chapter 2

Decentralised Data Fusion Systems

2.1 Introduction

The aim of this chapter is to provide detailed answers to the questions '*what* are the subject areas of the thesis?' and '*why* are they being investigated?' These will provide the requirements for the thesis, i.e. the *evaluation* and *application* of communications management in decentralised systems.

The mapping between these questions and the sections of this chapter are shown in Figure 2.1. Some of the more important issues in decentralised multi-sensor systems are outlined in Section 2.2. Developments in these areas are reviewed in Section 2.3. Possible sources and ways of dealing with bandwidth constraints within such systems are then described in Section 2.4. This leads to a more detailed review of communications within decentralised systems in Section 2.5. A possible engineering application area for these technologies is considered in Section 2.6. A summary and concluding remarks on the contribution this chapter makes to the dissertation are provided in Section 2.7. The *what* question is answered in Sections 2.2 to 2.6, the *why* question in Section 2.6.

2.2 Multi-Sensor Decentralised Systems

This section contains an introduction to decentralised systems, highlighting some of the important issues affecting them.

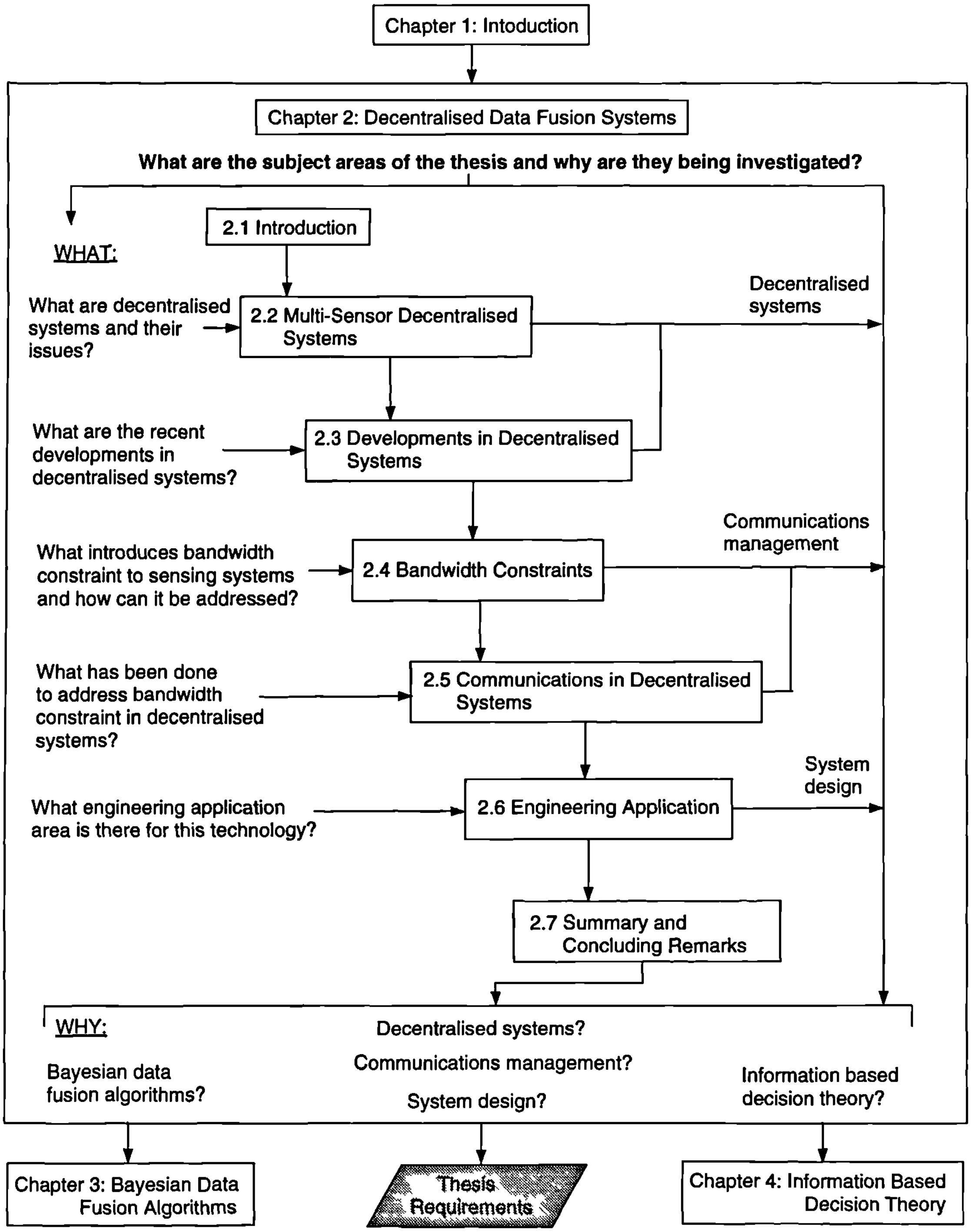


Figure 2.1: Reader's map for Chapter 2.

2.2.1 Decentralised Systems

Here we consider *fully decentralised* and *fully connected* sensing systems. By definition, this implies each sensor has an associated dedicated processing resource to form a processing node. In addition, each of these nodes can communicate directly with all other nodes of the system. Further details are available in the references of Section 2.3. The decentralised systems described in this thesis are characterised by the following criteria (Rao 1991):

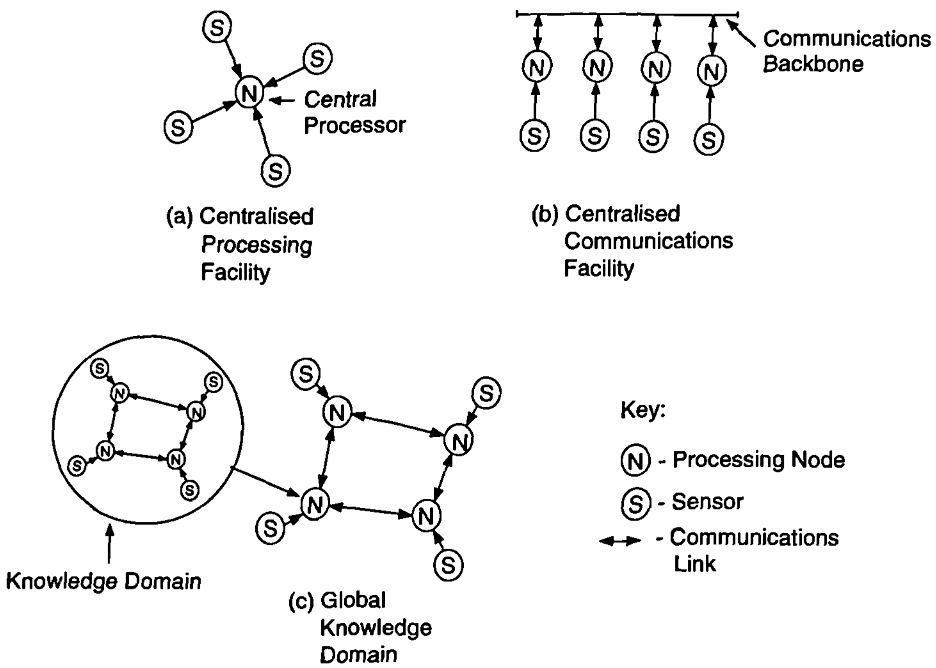


Figure 2.2: Characteristics that violate the decentralised philosophy.

1. **No central processing facility.** By definition a decentralised system does not employ a central processing facility. Truly decentralised systems communicate their 'local' sensor data to all other nodes. This leads to each processing node having a global view of the sensed environment. For a centralised system all sensor data is assimilated on a single central processor, see Figure 2.2(a). In comparison, decentralised systems provide graceful degradation in system performance, i.e. losing a single sensor, processor or communication link due to a fault results in the loss of data from that particular node *alone*. However, a single processor fault in a centralised system results in catastrophic failure, i.e. the system no longer functions.

2. **No central communications facility.** A truly decentralised system does not employ a central communications facility. Such communication facilities can result

in 'bottlenecks' which are brought about from contention for the bandwidth by the nodes. This reduces the system performance. Further, if a catastrophic fault occurs on such a central facility all inter-nodal communications may be lost. A system employing a central communications facility is represented in Figure 2.2(b).

3. **Total network knowledge is not required.** Each individual node in a decentralised system does not require knowledge of the complete sensing network. Such a requirement would inhibit the scalability and flexibility of the system. A system employing complete network knowledge is represented in Figure 2.2(c). By contrast, a node in a decentralised sensing system has knowledge only of the nodes to which it is connected by a communications link.

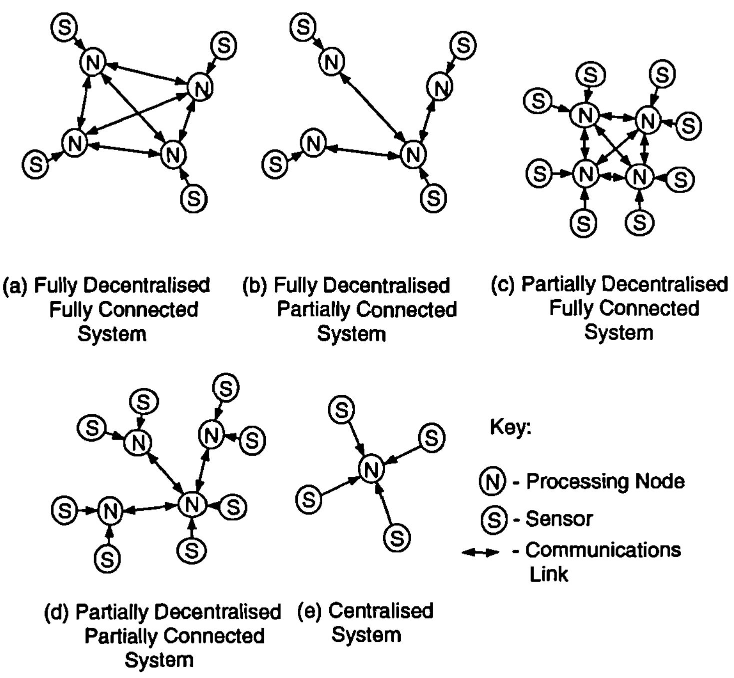


Figure 2.3: Decentralised and centralised systems.

Figures 2.3(a) to (e) represent a range of levels of decentralisation and connectivity between groups of sensors Ⓢ and processing nodes Ⓝ . Fully decentralised systems employ a processor with each sensor whereas partially decentralised systems have a single processor that deals with information from more than one sensor. Fully connected systems employ an individual communication link between each processing node whereas a partially connected system does not.

Decentralised systems offer a number of advantages over their centralised counterparts. These include increased survivability, extensibility, and a reduced communications requirement. These have been extensively reported (Rao et al. 1993, Berg 1993, Grime 1993). As such they are not documented here.

Decentralised systems offer the potential to revolutionise the design, operability, maintenance, and upgrading of products in many application areas, ranging from manufacturing to aerospace industries. System selection will depend on many factors, including application, performance and cost. The full range of decentralised/centralised architectures with their various advantages and disadvantages find applications accordingly.

2.2.2 Decentralised System Issues

The US Joint Director of Laboratories Data Fusion Subpanel (JDL-DFS) under the guidance of the US Department of Defence (DoD) have developed a generic processing model for data fusion (Waltz and Llinas 1991). This comprises four levels inter-connected as shown in Figure 2.4(a). For decentralised systems this model can be represented as in Figure 2.4(b). The work presented in this thesis is concerned with the level 4 issue of managing a communications resource in a decentralised system. In order to consider this management issue Level 1: Data Fusion also has to be investigated.

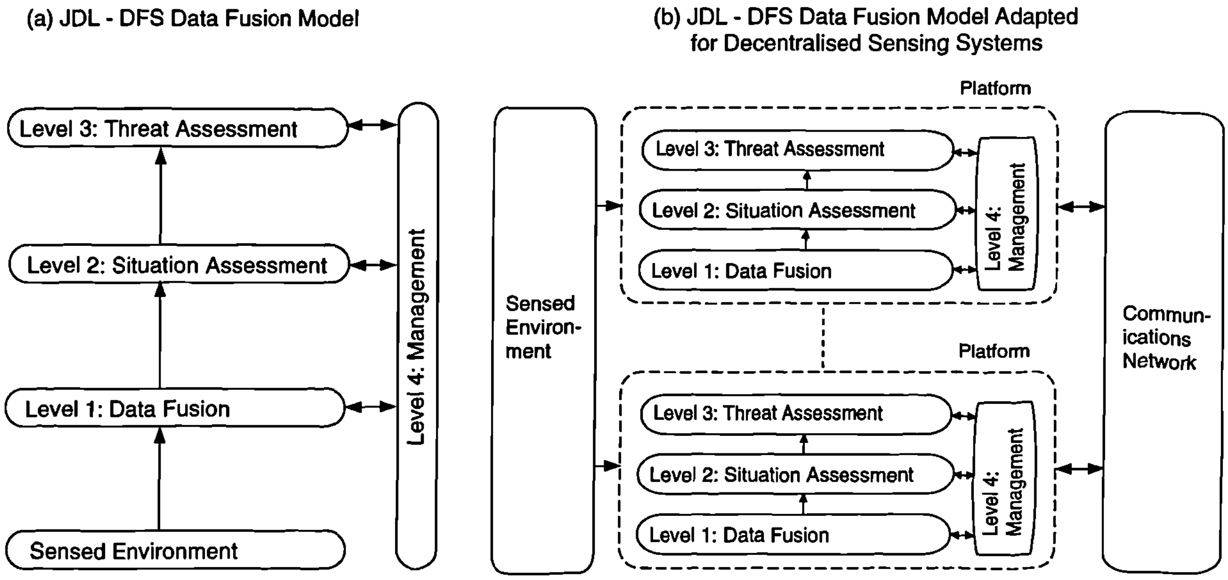


Figure 2.4: JDL-DFS data fusion model and its adaptation for decentralised systems.

Figure 2.5 represents some of the major research issues which affect the performance of a decentralised system. These individual issues are:

1. **Communication Issues:** The processing nodes of a decentralised system communicate with each other. An electronic communication system in its simplest form

comprises three components: a transmitter, a receiver and a communication medium. Many characteristics from each of these components contribute both to the bandwidth and latency of such a system. The bandwidth determines the amount of information that can be transmitted from the transmitter to the receiver in a given time period; the latency is the delay between the information being sent and received (Taub and Schilling 1987). To date, this is an area that has received relatively little research in the general area of data fusion. This is particularly true for decentralised systems. As such, researching this area ensures this thesis produces **original** work.

2. **Algorithm Issues:** The type of algorithm used in a decentralised system is dependent on the application and sensor employed. Popular tracking algorithms include the decentralised Kalman filter (DKF) in its state space or information form, with probabilistic (Bayes), evidential reasoning (Dempster-Shafer), and neural network algorithms being used for target identity fusion (Klein 1993). The algorithm issues also encompass other areas such as sensor models, process models and noise representation. In this thesis the decentralised information form of the tracking filter and Bayesian identification algorithms are employed to achieve Level 1: Data Fusion.

3. **Architecture Issues:** These are concerned with the type of processor, multiprocessor configuration (to achieve distributed and parallel processing), and the nodal topology (e.g. line, circle and tree). Further, the logical and physical implementation of the system have to be considered as they are often different. The architecture implemented will be influenced not only by the issues of Figure 2.5 but also by the overall system. For example, the choice of processors employed on an aircraft may be constrained for a number of reasons, e.g. power consumption and electromagnetic compatibility (EMC) requirements. In addition, a multiple aircraft scenario may be constrained, for tactical reasons, to a star topology with the hub of the star being the 'command' node, e.g. an airborne warning and control system (AWACS) (Lenk and Retzer 1997). This thesis employs a fully connected decentralised architecture.

4. **Planning Issues:** These include planning *missions* to achieve given *requirements* and determining the associated *costs*. For example, consider an aircraft planning its flight trajectory during which it has the *requirement* to identify several approaching target's with a limited sensor resource. Here the preferred trajectory carried out in order to identify the targets will be dependent on an associated *cost*. This may be measured, for example in the level of *fuel consumption* the aircraft experiences in carrying out the particular *mission* (Greenway et al. 1994). In this thesis trajectory planning is carried-out off line prior to running the simulation. As such, the platforms trajectories are not reactive to the targets behaviour and vice-versa.

5. **Management Issues:** The management of a system is primarily concerned with resources, e.g. communications management, sensor management, process management, and network management. Various strategies are available for dealing with such system management issues, for example utility functions and information theoretic approaches (Manyika and Durrant-Whyte 1994). It should also be noted when choosing a strategy that the various management issues may interact. This thesis is concerned with the information based management of a communications resource.

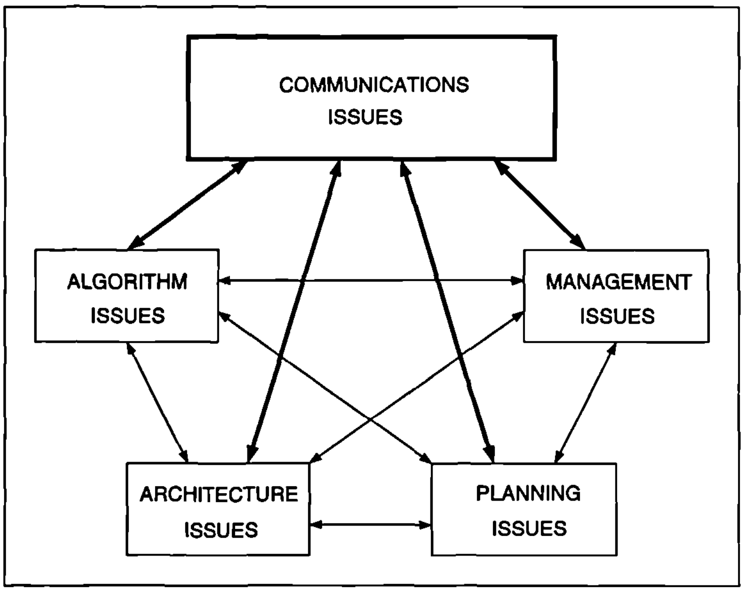


Figure 2.5: Communications and related issues in decentralised systems.

The benefits of decentralised systems include: modularity, scalability, flexibility, reduced communications requirements and increased survivability. This section has also answered the question 'what are the decentralised system issues?' The most important issues affecting them are: communications, algorithms, architectures, planning and management.

2.3 Developments in Decentralised Systems

This section aims to answer the question 'what are the recent developments in decentralised systems?' This is achieved primarily by documenting work carried out at SRC and Oxford University which are discussed in Sections 2.3.1 and 2.3.2 respectively. Details are also provided of related work being carried out at other institutions, see Section 2.3.3.

2.3.1 Sowerby Research Centre (SRC)

SRC have developed a 'data fusion test-bed' (DFTB) which is based on the work achieved in the ESPRIT Project SKIDS[1]. The system was developed under the guidance of Dr. P. Greenway (Greenway 1994b) (Greenway 1994a). Figure 2.6 (a) provides a pictorial representation of the SKIDS laboratory with a schematic plan view provided in (b). From the point of view of this work, the most important aspect of SKIDS was the first successful implementation of the decentralised Kalman filter (DKF), on a real time sensing and processing system operating on real data (Rao et al. 1993). Some of the general issues described in Section 2.2 have since been considered, and are described briefly next.

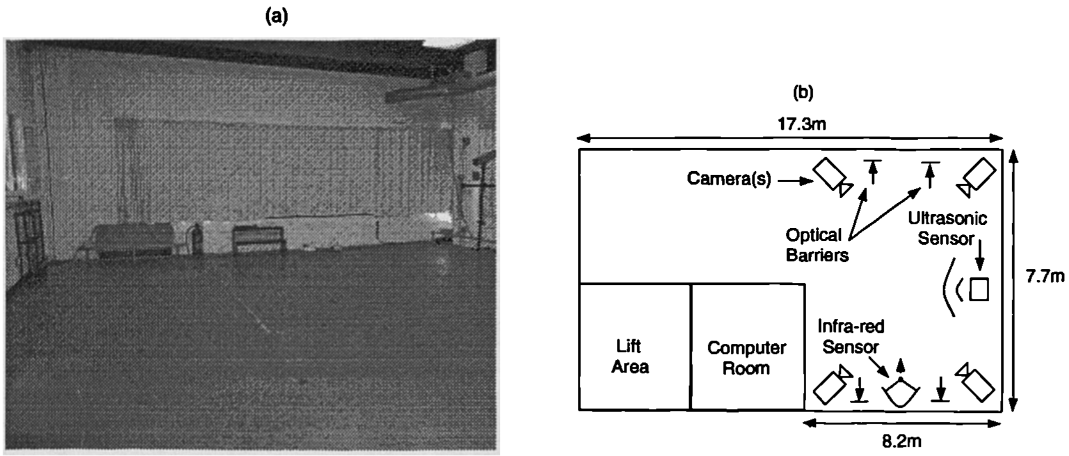


Figure 2.6: The SRC data fusion test bed (a) pictorial view (b) schematic of some of sensor positions.

Algorithm issues have been addressed: a distributed identity fusion system has been introduced onto the test-bed. This system is based on evidential reasoning. Here the targets identity is represented as two values, support for the target label and *one minus* support against the label. These are referred to as support logic pairs (SLOPs) (Baldwin 1985). A Dempster-Shafer rule was applied to combine SLOPs from different nodes. An alternative approach based on probabilistic theory has also been introduced. A comparison of these identity fusion methods has been carried out (Deaves and Greenway 1994b). This investigation showed that the computation required for the Bayesian algorithm was greater than that required for the evidential reasoning. However, the Bayesian algorithm converges quicker. A neural network classifier has been developed based on data generated from the test-bed (Caunce 1994). This system was able to identify 'novel' targets as well

[1]Signal and Knowledge Integration with Decisional Control for Multi-sensory Systems.

as those provided through the training set. Further, the work provided the potential for identifying different types of 'novel' targets by employing tight bounds on the activation regions generated by the training set data. Other statistical (Bayesian) target identification issues have been considered (Crowe et al. 1992). This work involved a detailed statistical analysis of the training set data to assist with feature selection, identification and weighting. The results of this analysis were applied to a neural network which performed the decision logic. Tracking, identification and sensor processing algorithms have also been investigated (Collins et al. 1997). This work involved image processing and feature selection/matching to a terrain database in order to obtain a platform localisation estimate. Further, this estimate was assimilated with an inertial platform estimate to improve the overall localisation estimate.

A variety of architecture issues have been investigated: these include the original SKIDS tracker (Rao et al. 1993), and a related machine vision architecture based on the Datacube (TM) hardware (Sheen and Greenway 1991). The DFTB architecture was extended with the introduction of two additional ultrasonic and infra-red based sensors to the system (Deaves 1993). These provided the system with pointable sensors that provided range only (or more precisely *nearly* range only data as bearing data could be inferred from the servo position) and bearing only data respectively. Figure 2.7 provides a pictorial representation of the infra-red and ultrasonic sensors.

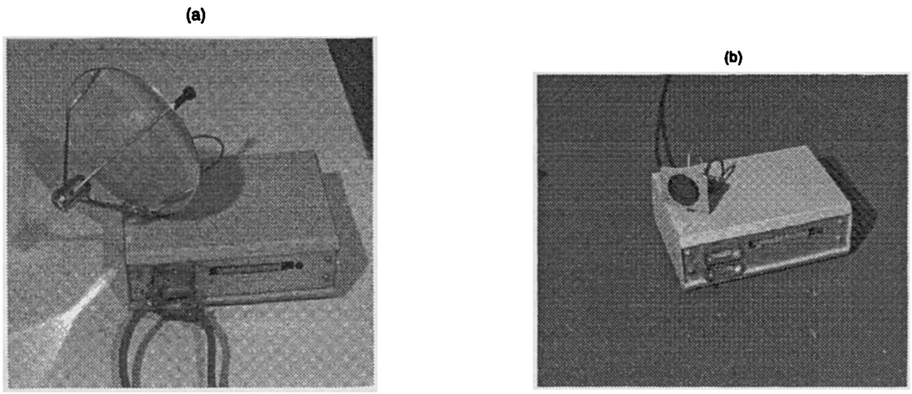


Figure 2.7: Infra-red (a) ultrasonic (b) sensors developed at Oxford University and implemented at the SRC.

Planning issues have been investigated (for example under the PANORAMA project), but have only recently been applied to the DFTB. This work was concerned with path planning given certain constraints such as fuel levels (Greenway et al. 1994). Here a robot was employed, i.e. the Robuter, to demonstrate the results obtained from the investigation in the SKIDS laboratory. Figure 2.8 provides a pictorial representation of the Robuter.

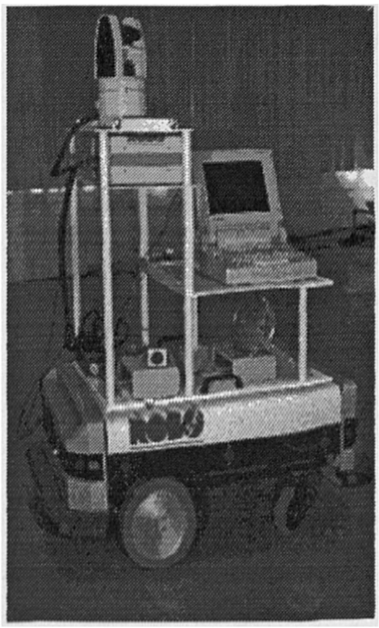


Figure 2.8: The Robuter at SRC.

Management issues have been investigated, initially using the DKF as an information filter for tracking based sensor-target assignment, and more recently building on this work and introducing a decentralised utility function for more complex assignments (Greenway and Deaves 1994a, Greenway and Deaves 1994b)[2]. Here the ultrasonic and infra-red sensors were employed to demonstrate decentralised sensor-target assignment.

2.3.2 Oxford University

Under the guidance of Professor H. Durrant-Whyte[3], some of the individual issues described in Section 2.2 have been addressed. However, it should be noted that much work relating to their interaction, as described in this thesis, still needs investigating to fully understand these systems.

Algorithm issues have been addressed. This includes work on the DKF and distributed identity fusion algorithm that contributed to the SKIDS tracker (Rao 1991). Further details on this work are provided in Section 2.5. The work on the DKF was further developed (Leonard and Durrant-Whyte 1992) and applied to mobile robot navigation using sonar. The problem of model distribution in decentralised multi-sensor systems has been investigated (Berg 1993). Here data from sensors observing different states was assimilated.

[2]This work follows that of Manyika and Durrant-Whyte, see Section 2.3.2.

[3]Durrant-Whyte has supervised the work of all the postgraduates mentioned in the next paragraphs. He now holds a chair at the University of Sydney.

The introduction and application of an information filter to decentralised systems was a key step (Mutambara and Durrant-Whyte 1994). This is a mathematical equivalent to the DKF, but is specified in a different form. This work also introduced non-linear filtering to decentralised systems. In (Mutambara and Durrant-Whyte 1994) distributed control of a modular scalable robot was achieved at a reduced inter-nodal communication cost and reduced computation by adaptively modelling the nodal behaviour. The information filter offers advantages when compared with the DKF. These include its ability to be used easily in non-fully connected topologies (Utete and Durrant-Whyte 1994b). This arises due to the computational advantage of the information filter during its *update* stage when compared with the Kalman filter. Another application of the information filter is for system fault detection (Gao and Durrant-Whyte 1994). Here a number of possible faults that could occur in a process plant were modelled. This was achieved by artificially introducing the fault and analysing the difference between the 'fault-free' system model and 'faulty' model. This allowed fault detection and, for some cases, fault identification using qualitative and quantitative techniques.

The architecture issues have been investigated through the development and application of the Locally Intelligent Sensor Agents (LISAs: A modular transputer based hardware architecture) (Grime et al. 1990). A similar architecture, the Locally Intelligent Control Architecture (LICA) was also developed (Hu et al. 1993) (this work was carried out under the guidance of Professor M. Brady). These comprised a processor (transputer), RS-422 inter-unit serial communication links, and 8-bit parallel ports for the control of transducers and sensors. These boards were packaged with power supplies, transducer pre-processing cards, and servo control cards to produce self-contained sensing nodes, e.g. the infra-red bearing only sensor described above (Grime 1993).

Planning issues, particularly fault detection and isolation, have been investigated by (Fernandez and Durrant-Whyte 1994). This work introduced a *recursive parameter estimator* with *adaptive forgetting* to isolate true faults from transients. Further, this parameter estimator could be used to predict when the faulty component needed replacing. Such an approach reduced the system down time by planning for shut downs. Reliability in decentralised networks (Utete and Durrant-Whyte 1994b) has also been investigated. This work was concerned with the introduction of dormant communication links to compensate for links that had failed. This approach employed *spanning distances* to plan which communication links to activate.

Management issues have been investigated through work on an information theoretic approach to sensor management. This work resulted in the publication of a standard textbook on this technological area (Manyika and Durrant-Whyte 1994). This work is investigated further in Section 2.5. The problem of network management has been investigated (Utete 1994, Utete and Durrant-Whyte 1994a). This work showed that decentralised systems employing loops in non-fully connected topologies lead to 'double data' counts that the channel filter could not combat. The organisation of decentralised nodes was investigated by (Ho 1994). Here the problem of how to connect nodes with a fixed number of communication links together in a loopless non-fully connected architecture to achieve a given system performance criteria was investigated. For example, identical nodes organised in a star topology provides the hub with better quality tracking estimates than those on the limbs.

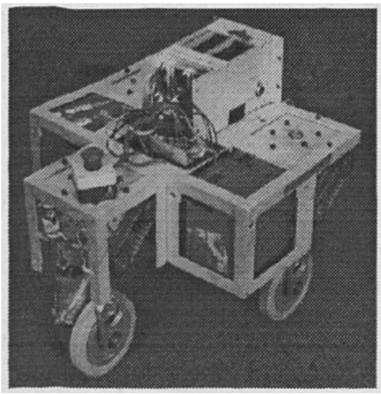


Figure 2.9: The Oxford University OxNav robot.

Communications issues have been investigated (Grime et al. 1990) and (Utete and Durrant-Whyte 1994a). Their investigations have resulted in the development of algorithms that reduce the number of communication links and bandwidth requirement in a system. Further details on this work are provided in Section 2.5. However, this work does not answer the question of 'given a limited communication resource, how should it be utilised?' This is the problem addressed in this thesis.

Applications of Oxford University's work include (Cooper and Durrant-Whyte 1994) which describes a high speed navigation system, modular mobile robots (Burke 1994), autonomous guided vehicles (Borthwick and Durrant-Whyte 1994) and a process plant simulation system (Gao and Durrant-Whyte 1991). Figure 2.9 provides a pictorial representation of the OxNav modular mobile robot.

2.3.3 Related Work

Many other industrial and academic institutions are researching areas that are relevant to decentralised sensing systems. Work carried out at some of these establishments is described below:

A large effort is being placed in the area of algorithm development. The acknowledged world expert in target tracking and data association, Professor Y. Bar-Shalom, who is based at the University of Connecticut in the USA, has been and is pursuing a number tracking and data association algorithms. He is joint author of a number of standard text-books on the subject (Bar-Shalom 1992a, Bar-Shalom 1992b, Bar-Shalom and Li 1993) and has pioneered many of the key ideas and concepts. This work includes the use of interactive multiple models (Bar-Shalom et al. 1989), investigations into common process noise (Bar-Shalom and Campo 1986) and track-to-track fusion techniques (Bar-Shalom 1981).

The application of fuzzy logic to the areas of data fusion algorithms have been investigated at Southampton University under the guidance of Professor C. Harris (Harris 1996) and at Siemens Plessey Systems (Noyes 1998). The work of Southampton University has been applied to the aerospace industry for obstacle avoidance in helicopter applications. This requires a platform localisation and navigation capability. The Defence Evaluation Research Agency (DERA) are currently investigating a number of novel algorithm issues. These include the bootstrap (Gordon 1996) and hybrid (Black and Reed 1996) algorithms to overcome problems associated with non-linear systems and non-Gaussian noise sources. The bootstrap algorithm aims to obtain the non-linear system state transition characteristics through system sampling on-line. The hybrid algorithm overcomes non-Gaussian noise sources through representing that noise with a number of Gaussian sources of different mean and standard deviation. It is then possible to carry out the prediction stage by employing multiple Gaussian filters.

Two other novel approaches are being investigated. The first is for tracking non-linear systems, i.e. the distribution approximation filter (DAF), and another for correlated track fusion, the covariance intersection (CI) filter. The DAF is simple to implement, according to its developers (Julier et al. 1995), and is claimed to out perform the extended Kalman filter (EKF)[4]. This algorithm employs an optimum number of points to represent the non-linear state transition. It is claimed that this provides a state transition that is better than that obtained by the EKF and approaches that obtained by more computationally expensive algorithms such as the bootstrap algorithm. The CI algorithm is employed when nothing is known about the correlation between an observation (or track) and a track. Here the information states and the corresponding information covariances of the observation (or track) and track are appropriately weighted to satisfy some criteria, e.g. minimising the determinant of the resulting covariance. This provides an upper bound on the resulting covariance by assuming that the observation (or track) and track were

[4]The most commonly used filter to deal with non-linear systems. This EKF works on the principle of linearising the system between limits.

strongly correlated.

(Wadsworth 1995) documents developments in track-to-track fusion techniques. Further, this work described a generic track fusion technique which accounts for correlations in the track data, data latency, differing update rates, and track formation and detection in a natural manner. This is achieved at a slightly sub-optimal trajectory estimation performance. Research in the area of target identification algorithms is being pursued by the DERA under the NEMISIS project (Griffith 1997). This work was based on trials at RAF Valley, North Wales, on identifying military aircraft.

Architectural issues within data fusion have been investigated (Ding and Hong 1996), (McKee 1994). Much of this work is based on operating sensing systems with man-in-the-loop control systems. The difficulty is increased for this work since the sensing system and the man are not co-located. Most of the work in this area is concerned with distributed (or hierarchical) topologies, with very little work being carried out on decentralised architectures. A common mistake within the data fusion community is to refer to distributed systems as being decentralised (Pucar and Norberg 1997). This can be the cause of ambiguity. A recent survey of distributed sensing systems indicates that this is an area of on-going research (Chong 1998, Zhu et al. 1998, Nechval 1998).

Planning issues, with particular emphasis on command, control, communication and intelligence (C^3I), is being investigated by K. Hintz at the George Mason University (GMU) in the USA. Hintz may rightfully be able to lay claim to being the first to apply an information theoretic approach to resource management in data fusion systems (Hintz and McVey 1991). However, some theoretical problems associated with the *conforming matrix* applied in this work was highlighted by Kastella (Kastella 1997). Hintz also maintains a World Wide Web site devoted to sensor management (Hintz 1996). Work in the area of C^3I situation assessment is also being carried-out at the DERA (Farmer 1997a, Farmer 1997b). System sensor evaluation and selection has been investigated by C. Noonan of BAe Military Aircraft and Aerostructures. Here entropy is used as an information measure to access the performance of a multi-sensor configurations for military aircraft scenarios (Noonan 1996).

Work on management issues are being investigated by K. Kastella of Lockheed-Martin USA (Kastella and Biscuso 1995, Kastella and Lutes 1995, Copeland and Kastella 1995). The main focus of this work has been in the area of sensor management, particularly the aspect of sensor-target assignment in the military domain.

Communications within decentralised systems is the area which appears to have received least consideration within the data fusion community. Recently Professor Y. Bar-Shalom's group, under US Air Force funding, have started to examine communications issues in centralised tracking systems (Alford et al. 1996). Other researchers under US

Air Force funding are also investigating this area (Kadar and Liggins 1997). This emphasises the importance the military place on this area. Compression/reduced resolution techniques for communications in centralised tracking systems have also been investigated (Olivier et al. 1995). Here a lookup table is used to convert a measurement vector to another vector of smaller dimension which has approximately the same information content. Another approach used for dealing with bandwidth constraint in centralised sensing systems is described in (Wong et al. 1998). In this work wavelet decomposition is employed to reduced the size of the data for transmission by suppressing insignificant side bands. This approach also claims the benefit of requiring less processing for data fusion since the data size is smaller. Recently, the DERA have began to investigate the effect of reducing the resolution of identification information in a bandwidth limited channel (Black and Bedworth 1998).

Communications issues are also being investigated in non-military multi-agent applications (Stone and Veloso 1998). In this work two teams (in fact, robot football teams) contend for the same communication resource with fairly sophisticated abilities, e.g. potential for communicating decoy messages. In addition, the Centre for Communications Research of the Department of Electrical and Electronic Engineering of Bristol University have began to investigate this area. This has been stimulated by the close working relationship set up between Professor D. Bull and SRC (Deaves et al. 1996).

In summary, little work has been carried-out on the effects of reduced communications bandwidth in multi-sensor systems. Further, even less work has been focussed on addressing this problem. This is particularly true for decentralised systems where the management of bandwidth limited communications channels appears to have received no research effort until the production of this thesis.

Since 1995 Professor H. Durrant-Whyte has lead the Department of Mechanical and Mechatronic Engineering at the University of Sydney. Current work has focussed on the application of data fusion techniques to the mining industry. The navigation of an under ground vehicle is described in (Scheding et al. 1997). In (Newman and Durrant-Whyte 1996) the application of data fusion to underwater applications is described. Here an acoustic sensor is employed for localisation and obstacle avoidance. The work described in (Durrant-Whyte et al. 1995) is based on the localisation and navigation of ship unloading vehicles. This work has focussed on demonstrating the maturity of data fusion techniques for commercial applications. However, theoretical work on a variety of other topics is also being maintained. For example advanced tracking algorithms (Julier et al. 1995), applications for the localisation and navigation of space craft (Quine et al. 1996), advanced map building techniques which employ *relative* filters in order to reduce computational work load (Csorba and Durrant-Whyte 1997), and sensor technologies including the development of a milli-metre wave radar (Clark and Durrant-Whyte 1997) for application on mining vehicles. In addition, Professor H. Durrant-Whyte maintains his position as a recognised world expert in theoretical and practical issues of decentralised systems through continued work in this technological area (Durrant-Whyte et al. 1998).

This section has answered the question 'what are the recent developments in decentralised systems?' This indicates that, to date, not much research effort has been placed on investigating the effects of bandwidth constraints in decentralised sensing systems. Further, techniques for managing a communications resource in a decentralised sensing system has received even less, if any, research effort (until the publication of this thesis). However, researchers in the general data fusion community are awakening to the potential of distributed/decentralised systems and the problem of limited communications resources. The most prominent of these being Professor Y. Bar-Shalom, arguably the world's leading figure in data fusion, under USAF funding, the largest air force in the world.

2.4 Bandwidth Constraints

In this section we answer the questions 'what introduces bandwidth constraint to sensing systems and how can it be addressed?'

2.4.1 Sources of Bandwidth Constraints

Communications systems comprise three individual components: a transmitter, a receiver, and a transmission medium. In electronic communications systems the *maximum transmission bandwidth* is dependent on all three components. This value is given by the *Hartley-Shannon* equation and is related to the signal-to-noise ratio (SNR). The higher the SNR the higher the *maximum transmission bandwidth.* However, the *available bandwidth* may be constrained to be less than this maximum value due to system requirements. Sources of bandwidth constraint include:

1. **Hostile environments:** If the decentralised system is working in a hostile environment where electromagnetic noise has a high level the bandwidth of the electronic communications system may be less than if it were operating with low noise levels. This is especially true in battlefield environments where smoke reduces the available system communications bandwidth (Van-de Wal 1993) by increasing the system noise, which reduces the SNR.

2. **Low emission applications:** Some systems will be required to operate under the constraint of giving off low levels of electromagnetic radiation. Hence, in order to achieve this requirement the electronic communication system will reduce its emissions which results in a reduced communications bandwidth. This situation arises since the signal level is reduced, which reduces the SNR, which reduces the *maximum transmission bandwidth.* This is especially true in battlespace environments where aircraft have a requirement to reduce their probability of detection (Windel 1996).
3. **Large number of targets:** If the system is viewing a large number of targets this implies that a large amount of data will need to be communicated. Under such circumstances the communications system may not be able to transmit all the data in the given communication time slot. Therefore the available communications bandwidth for each target is constrained (assuming that *maximum transmission bandwidth* remains fixed) (Heliotis 1995).
4. **Large number of processing nodes:** In systems where the available bandwidth is shared amongst the processing nodes, the larger the number of nodes the less will be the communications bandwidth available for each individual node (assuming the *maximum transmission bandwidth* remains fixed) (Heliotis 1995).
5. **High data rate sensors:** If sensors which provide large amounts of data are employed, for example image sensors, the update rate that can be achieved over a communication channel may be low (Gartner and Schneider 1996). This implies that the communications bandwidth available for each individual sensor will be constrained (assuming the *maximum transmission bandwidth* remains fixed).
6. **High target data levels:** If the information generated on a target is large in quantity this leads to a similar situation as that found for *High data rate sensors.*

Bandwidth constraint in sensing systems can lead to the problem that not all the data that is required to be transmitted can be communicated.

2.4.2 Dealing with Bandwidth Constraint

The *available* bandwidth between processing nodes can be utilised by employing signal processing techniques. Some of these are discussed below:

1. **Lossless Data Compression:** This technique takes a quantity of uncompressed data and compresses it, without loss of salient information, to a fraction of its original size. This compressed data is then communicated from the transmitter to the receiver via the communications medium. A process at the receiver then uncompresses the data. Examples of techniques that can provide compression include the

discrete cosine transform and the Walsh transform (Ifeachor and Jervis 1993). Lossless methods have the advantage that the original data can be fully reproduced at the receiver, but has the disadvantages that the system is not scalable, i.e. cannot cope with an increase in data rate, and that the compression and uncompression techniques can be computationally expensive (requiring expensive processors and introducing latency effects to the system).

2. **Distributed Information Loss:** Here the information loss is distributed evenly across the complete data set to be transmitted by reducing the resolution of each item of data. For example, consider the following system: $1k$ of data are to be transmitted per second, with each item of data comprising 4 bytes, hence a bandwidth of $4k$bytes per second is required. Unfortunately, the available bandwidth is only $3k$bytes per second. Therefore for this method all the items of data are communicated with the omission of the least significant byte. This reduces the data rate to that of the available bandwidth. The main advantages of this system is that information on all data items is transmitted and that the process is computationally in-expensive. The main disadvantage is that a loss of resolution is experienced by the data (Black and Bedworth 1998). In extreme cases this can lead to the generation of an incorrect estimate. Again, this approach is not scalable.

3. **Selected Data Transmission:** Here items from the data set are selected so as to fill the available bandwidth. This is achieved by not transmitting certain items of data. Again, using the previous example, a decision algorithm is used to choose the data for transmission. It should be noted that a different 75% of data can be transmitted each time. The advantage of this method is that it is scalable, and may be computationally in-expensive. The main disadvantage of this method is that some items of data are not communicated at all[5]. Such selective methods have been applied for sensor management in decentralised systems (Manyika and Durrant-Whyte 1994).

The computational requirements and lack of scalability inherent in lossless compression techniques make them unsuitable for application in decentralised communications management. Distributed information loss can lead to over and under estimates, e.g. in the identity and location of targets, from which there is no recovery. Further, this technique is not scalable. Therefore, distributed information loss is not suitable for application in decentralised communications management. The selected data transmission technique suffers from the problem of introducing data latency or delays. However, given the problems associated with the other techniques coupled with the fact that a selected

[5]This is not always the case since in some systems data can be accumulated before being transmitted. In this case the disadvantage manifests itself as a data latency.

data technique has been applied to sensor management, a research effort into selected data transmission is justified.

> This section has answered the questions 'what introduces bandwidth constraint to sensing systems, and how can it be addressed?' This has been achieved by providing details of the causes of bandwidth constraint, i.e. hostile environments, low emission applications, large numbers of targets, large numbers of processing nodes, high data rate sensors and high target data levels, and methods of addressing it, i.e. lossless compression, reduced resolution data, and data selection. Further, a research effort into a data selection method for communications management in decentralised systems has been vindicated.

2.5 Communications in Decentralised Systems

Here we answer the question 'what has been done to address bandwidth constraint in decentralised systems?' This is achieved by reviewing in greater detail the work relevant to communications within decentralised sensing systems. Further, research that has been carried-out on decentralised systems that can be applied to the investigations of this dissertation are identified.

2.5.1 Communications Development

The work in (Grime 1993) was to develop a non-fully connected and fully decentralised topology and algorithm, which had a reduced communications requirement.

Figure 2.10(a) 'Circular Connection' represents the information flow that occurs in a 3-node fully connected fully decentralised system after each sensing node has made an observation. For this system six communications take place i.e. $N \times (N - 1)$ where N is the number of nodes. This circular connection can be mapped onto a line connection as represented in Figure 2.10(a) 'Line Connection'. This is the implementation employed in the DKF of the SKIDS tracker (Rao et al. 1993). Here the sensing nodes (N1, N2, N3) have been modified slightly (N'1, N'2, N'3) to deal with this 'broadcast' communications. The logical implementation is fully connected whereas the physical implementation is partially connected. It should be noted that the number of items of data communicated has remained unchanged.

Figure 2.10(b) represents the results of their work. Here a non-fully connected and fully decentralised topology is implemented. The algorithm used allows the combination of items of data before communication e.g. $I(1)$ and $I(2)$ are combined by employing a Bayesian based data fusion algorithm to give the single datum $(I(1) + I(2))$. Here the

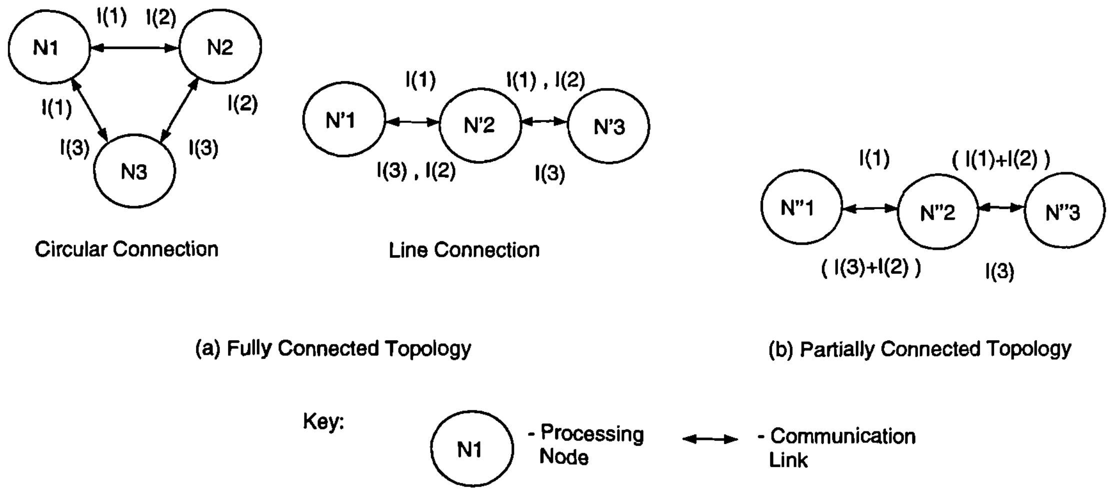


Figure 2.10: Fully and non-fully connected topologies.

size of $I(1)$, $I(2)$ and $(I(1) + I(2))$ are all equal. Hence the number of items of data that need to be communicated has reduced from 6 to 4, i.e. 2.(N-1). This is achieved using the modified processing nodes (N"1, N"2, N"3). Therefore, it was shown how the use of appropriate topologies and resulting algorithms can produce a reduced communications bandwidth requirement.

This work showed that employing a non-fully connected decentralised system could result in a reduced communications bandwidth requirement. However, the work did not investigate the issue of how to manage a communication system with a constrained bandwidth. This is the subject area of this dissertation, i.e. communications management in decentralised systems.

2.5.2 Algorithm Development

The work described here uses the decentralised data fusion algorithms first documented in the paper (Rao and Durrant-Whyte 1991) and thesis (Rao 1991). This involved the development and implementation of fully connected, fully decentralised identification and tracking algorithms. The identification algorithm was based on Bayes theorem and the tracking algorithm on a Kalman filter (also derived from Bayes theorem). It was shown that the decentralised versions of the algorithms were mathematically equivalent to their centralised counterparts. Recent tracking algorithm implementations have focussed on the use of the decentralised information filter which can be more computationally efficient than the DKF (Grime 1993). These algorithms have been applied in the work of other researchers (Utete 1994) (Ho 1994) (Manyika and Durrant-Whyte 1994). Since these Bayesian based data fusion algorithms have been employed and verified in a number of decentralised systems research projects they are applied to the work documented in this dissertation.

2.5.3 Management Development

The information theoretic approach applied to decentralised data fusion sensor management (Manyika and Durrant-Whyte 1994) is employed as a basis for the management of communications in this thesis.

For their work a practical system based on a robotic application was used to verify the theoretical results. The robot was equipped with three servo mounted ultrasonic sensors and was made to move in an environment in which there were multiple targets. The objective of the sensor management algorithm was to carry out the sensor-target assignment so as to maximise the overall positional information about those targets. The results of these experiments may be found in (Manyika and Durrant-Whyte 1994). This work also employed sensor management for feature identification. These investigations showed that an information theoretic approach could be usefully applied to sensor management.

Here, we propose to extend this information theoretic approach to communications management. It will be applied to the data selection method of dealing with a bandwidth constraint. This provides the desirable potential for compatibility with other resource management areas and is a first, tentative step, towards a unified theory of resource management within data fusion systems.

> This section has answered the question 'what has been done to address bandwidth constraint in decentralised systems?' This indicated that a data selection method for communications management had not previously been investigated within the technology area of decentralised sensing systems. This motivates the research area of this dissertation, i.e. communications management in decentralised sensing systems, as it is an **original** research area. Futher, previous work applicable to the investigations of the thesis was identified. These included Bayesian data fusion algorithms, justified on the basis that they have been successfully employed in numerous other decentralised sensing systems research projects, and an information theoretic approach to decision making, appropriate on the basis that it has been successfully applied to sensor management.

2.6 Engineering Application

This section considers the engineering application potential of decentralised sensing systems in the aerospace industry.

2.6.1 General Aerospace Requirements for the Future

A NATO advisory group has been formed to forecast technologies that will play key roles in the Aerospace industry during the next twenty five years. In a recent report (Timmers and Ott 1997) they identified modular avionics as one such important area:

'Avionics is approaching 40% of the weight and cost of an aircraft. In order to reduce weight, cost and maintenance actions and provide affordably increased functionality, a highly integrated commercial-off-the-shelf (COTS) based avionics architecture must be developed. This architecture will be characterised by its modularity, resource sharing, fault tolerance attributes and wide use of commercial components.'

Decentralised systems offer the potential for realising some of these characteristics in avionic systems of the next generation. This observation provides a commercial motivation for researching decentralised systems.

2.6.2 Design Engineering

British Aerospace Military Aircraft and Aerostructures is a world leader in the design, manufacture and support of a broad range of military aircraft and aircraft assemblies (BAe 1998). Further, a state-of-the-art in fully integrated avionics/weapons capability from initial rapid prototyping and concept design through design, development and testing has been achieved through participation in projects such as Eurofighter.

In order for British Aerospace to maintain this position it is vital to continue research in these areas. This motivates the application of the results of this research to an avionic system design problem.

> This section has answered the question 'what engineering application area is there for this technology?' A NATO survey into the future requirements of the aerospace industry in the next twenty five years identified the next generation of avionic systems as an important research area. Further, research into design engineering techniques will contribute to maintaining BAe's role as a world leader in the aerospace industry. These points motivate the engineering application of decentralised systems to the design of avionic systems.

2.7 Summary and Concluding Remarks

We began this chapter by stating a number of questions derived from 'what are the subject areas of the thesis?' These have been answered in the preceding sections of this chapter. Here these are used to answer the following important question 'why are they being investigated?'

- *'Why decentralised systems?'*
  Decentralised systems offer a number of potential advantages over their centralised counterpart. These include modularity, scalability, flexibility, survivability and a reduced communications requirement. These advantages motivate a research effort into the general area of decentralised systems.
- *'Why communications management?'*
  A review of research in the area of decentralised sensing systems indicated that only a limited research effort had been applied to investigating communications issues in decentralised systems. Further, no research effort had been placed on using a data selection method for communications management. This makes the subject area of the thesis **original**. However, the *importance* of managing a limited communications resource has been realised and is starting to be investigated by a number of data fusion researchers.
- *'Why system design?'*
  The problem area of designing future avionic systems has been identified, through a literature review, to be very important for the aerospace industry. This makes the engineering application area of the dissertation, i.e. system design, very **relevant** to the needs of BAe[6].
- *'Why Bayesian data fusion algorithms?'*
  These algorithms have been used extensively in the general area of data fusion. Further, they have been applied successfully in a number of decentralised systems research projects. As such, their use in the work of this dissertation is vindicated. (Further details of these algorithms are provided in Chapter 3.)
- *'Why information based decision theory?'*
  Information based decision theory has been successfully applied to the task of decentralised sensor management. Therefore, the application of this theoretical technique to decentralised communications management is a natural progression. Further, this approach offers the desirable characteristic of compatibility. (Further details of this subject area are provided in Chapter 4.)

[6]The company which employs the author.

The answers to these question provide the requirements for the thesis. These are stated as:

1. Design, build, test and implementation of a decentralised multi-sensor multi-target system.
2. Use this to *evaluate* an information theoretic approach to communications management and provide support to **Proposition 1** (see page 1) of the thesis.
3. Finally, *apply* the results of the investigation to the engineering application area of decentralised avionic design and provide support to **Proposition 2** (see page 1) of the thesis.

Chapter 3

Decentralised Bayesian Data Fusion Algorithms

3.1 Introduction

The aims of this chapter are to answer the questions '*what* are the decentralised Bayesian data fusion algorithms used for this thesis?' and '*why* are they being employed?' These answers will provide the infrastructure capability for the thesis. Readers familiar with this topic may omit this chapter on a first reading.

The mapping between these questions and sections of the chapter are provided in Figure 3.1. Section 3.2 provides a brief review of Bayes' theorem. Section 3.3 states the kinematic and identity estimators used for this thesis. Section 3.4 describes how these data fusion algorithms are applied to fully decentralised and fully connected systems. Section 3.5 discusses some connectivity issues in decentralised systems. Section 3.6 describes the application of channel filters to bandwidth constrained communication links. A summary and concluding remarks are provided in Section 3.7. This leads to a statement of the infrastructure capabilities used for this thesis. The *what* question is answered in Sections 3.2 to 3.6, the *why* question in Section 3.7.

3.2 The Bayesian Paradigm

This section aims to answer the question 'what is the link between Bayes theorem and data fusion?' This is achieved by a brief historical note on Bayes theorem followed by its

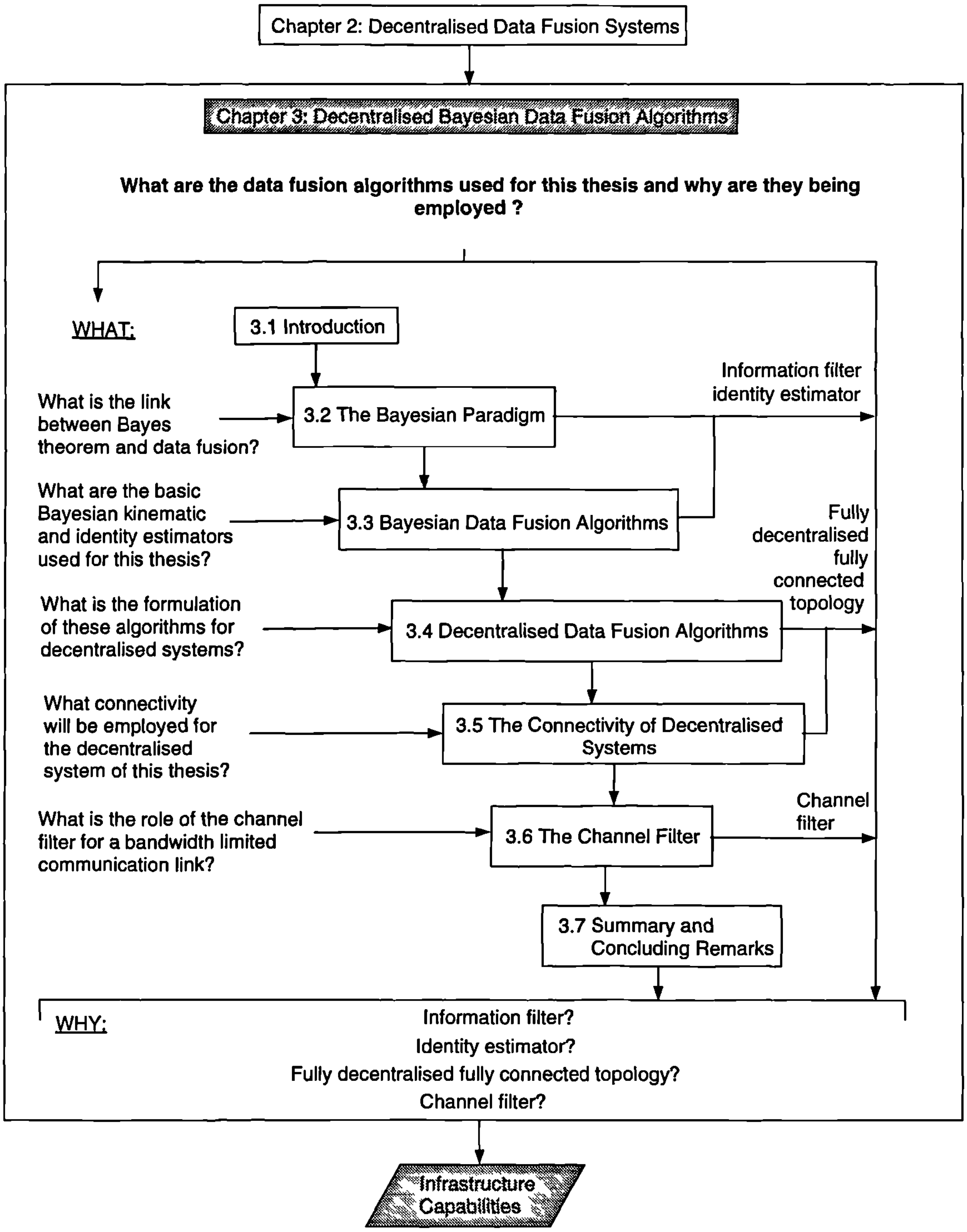


Figure 3.1: Reader's map for Chapter 3.

definition and application to data fusion.

3.2.1 Historical Note

Bayes' Theorem was first reported in the Royal Society Proceedings of December 1763 by Mr. Price who wished to document the work of the recently deceased Rev. Bayes (Bayes 1763)[1].

Bayesian statistics has been widely applied within the data fusion community. The basis for this is explored below.

3.2.2 Bayes' Theorem and Data Fusion

Bayes' theorem provides a method of combining data. From conditional probability theory:

$$P(\mathbf{X},\mathbf{Z}) = P(\mathbf{Z}|\mathbf{X}) \times P(\mathbf{X}), \tag{3.1}$$

$$P(\mathbf{Z},\mathbf{X}) = P(\mathbf{X}|\mathbf{Z}) \times P(\mathbf{Z}) \tag{3.2}$$

and

$$P(\mathbf{Z},\mathbf{X}) \equiv P(\mathbf{X},\mathbf{Z}). \tag{3.3}$$

Combining Equation 3.1, 3.2 and 3.3 gives Bayes rule. This is defined in Equation 3.4:

$$P(\mathbf{X}|\mathbf{Z}) = \frac{P(\mathbf{Z}|\mathbf{X}) \times P(\mathbf{X})}{P(\mathbf{Z})}, \tag{3.4}$$

where

$\mathbf{Z}$	-	A set of events, e.g. toss of a coin.
$\mathbf{X}$	-	A set of states, e.g. outcome of a game.
$P(\mathbf{X}\|\mathbf{Z})$	-	The state estimates for $\mathbf{X}$ after $\mathbf{Z}$ events.
$P(\mathbf{Z}\|\mathbf{X})$	-	The probability of the event set $\mathbf{Z}$ given the states $\mathbf{X}$.
$P(\mathbf{X})$	-	The prior unconditional probability for the states $\mathbf{X}$.
$P(\mathbf{Z})$	-	The unconditional probability of the set of events $\mathbf{Z}$.
$P(\mathbf{X},\mathbf{Z})$	-	The unconditional probability of event $\mathbf{X}$ and $\mathbf{Z}$.

[1]This paper is not recommended for reading as the scientific presentation and English of 1763 is difficult to follow!

The probability of an event is:

$$P(\mathbf{Z}) = \sum_{\forall \mathbf{X}} P(\mathbf{Z}|\mathbf{X}) \times P(\mathbf{X}), \tag{3.5}$$

which in equation 3.4 is often a normalising constant.

Bayes' theorem can also be represented in recursive form:

$$P(\mathbf{X}|\mathbf{Z}^k) = P(\mathbf{X}|\mathbf{Z}^{k-1}) \times P(Z(k)|\mathbf{X}) \times \alpha_k, \tag{3.6}$$

where

$\mathbf{Z}^k$	-	A set of (uncorrelated) events $\{Z(1), Z(2), \ldots Z(k)\}$.
$\mathbf{Z}^{k-1}$	-	A set of (uncorrelated) events $\{Z(1), Z(2), \ldots Z(k-1)\}$.
$Z(k)$	-	An event at index k.
α_k	-	A normalising constant.

For the data fusion considered for this thesis the continuous states are concerned with the kinematics of a target and the discrete states are concerned with a targets identity. These are discussed in more detail in the next section. Further, events are generated from sensors and are defined as ***observations***.

The kinematic estimation algorithm (Manyika and Durrant-Whyte 1994) for this thesis comprises three stages. Firstly, a *predict* stage is used to determine the state of the system based on the previous estimation or *update*, i.e. $p(\mathbf{x}|\mathbf{z}^{k-1})$. This is followed by an *observation* stage, where the sensor data is processed, i.e. $p(z(k)|\mathbf{x})$. The final stage of the algorithm is the *update* stage where the *prediction* data and *observation* data are assimilated, i.e. the generation of $p(\mathbf{x}|\mathbf{z}^k)$. The cycle then repeats.

The identity estimation algorithm (Rao et al. 1993) for this thesis comprises two stages. Firstly, an *observation* stage processes the sensor data, i.e. $P(Z(k)|\mathbf{X})$. This is followed by an *update* stage where the *observation* and previous *update*, i.e $P(\mathbf{X}|\mathbf{Z}^{k-1})$, are assimilated to provide the current *update*, i.e. $P(\mathbf{X}|\mathbf{Z}^k)$. The cycle then repeats.

This section has presented an historical review of Bayes' theorem which leads to its definition. Further, brief details of the application of Bayes' theorem to a kinematic estimation algorithm and an identity estimation algorithm were provided.

3.3 Bayesian Data Fusion Algorithms

Here we answer the question 'what are the basic Bayesian kinematic and identity estimators used for this thesis?' This is achieved by stating both the kinematic, i.e. information filter, and identity estimators for a single target and single sensor scenario.

3.3.1 A Kinematic Estimator: The Information Filter

The kinematic estimator employed for this thesis is the information filter. A number of books, e.g. (Manyika and Durrant-Whyte 1994) and theses, e.g. (Grime 1993) have published the filter derivation. Hence it is not provided in this dissertation.

The filtering algorithm (Maybeck 1979) is summarised in Table 3.1.

The Linear Information Filter

Prediction

$$\hat{\mathbf{Y}}(k|k-1) = [\mathbf{F}(k)\tilde{\mathbf{Y}}^{-1}(k-1|k-1)\mathbf{F}^T(k) + \mathbf{Q}(k)]^{-1}$$
$$\hat{\mathbf{y}}(k|k-1) = \hat{\mathbf{Y}}(k|k-1)\mathbf{F}(k)\tilde{\mathbf{Y}}^{-1}(k-1|k-1)\tilde{\mathbf{y}}(k-1|k-1)$$

Observation

$$\mathbf{i}(k) = \mathbf{H}^T(k)\mathbf{R}^{-1}(k)\mathbf{z}(k)$$
$$\mathbf{I}(k) = \mathbf{H}^T(k)\mathbf{R}^{-1}(k)\mathbf{H}(k)$$

Update

$$\tilde{\mathbf{y}}(k|k) = \hat{\mathbf{y}}(k|k-1) + \mathbf{i}(k)$$
$$\tilde{\mathbf{Y}}(k|k) = \hat{\mathbf{Y}}(k|k-1) + \mathbf{I}(k)$$

Table 3.1: Information filter equations.

where the variables have their usual meaning (Manyika and Durrant-Whyte 1994):

$\tilde{\mathbf{y}}(k\|k)$	-	The information state estimate vector at time index k.
$\hat{\mathbf{y}}(k\|k-1)$	-	The information state prediction vector at time index k given the data at time index $k-1$.
$\tilde{\mathbf{Y}}(k\|k)$	-	The information state estimate covariance matrix at time index k.
$\hat{\mathbf{Y}}(k\|k-1)$	-	The information state prediction covariance matrix at time index k given the data at time index $k-1$.
$\mathbf{F}(k)$	-	The state space transition matrix at time index k.
$\mathbf{z}(k)$	-	The observation vector at time index k.
$\mathbf{H}(k)$	-	The observation model matrix at time index k.
$\mathbf{R}(k)$	-	The observation covariance matrix at time index k.

Further, for constant velocity targets (Bar-Shalom and Li 1993):

$$\mathbf{F}(k) = \begin{bmatrix} 1 & \Delta T \\ 0 & 1 \end{bmatrix} \quad \text{and} \quad \mathbf{Q}(k) = \begin{bmatrix} \frac{\Delta T^4}{4} & \frac{\Delta T^3}{2} \\ \frac{\Delta T^3}{2} & T^2 \end{bmatrix} \times q \tag{3.7}$$

where ΔT is the time interval between two consecutive updates and q is process variance.

It should be noted that the information states of the kinematic estimators can be converted to the state space using the following equations:

$$\mathbf{x}(i|j) = \mathbf{Y}^{-1}(i|j)\mathbf{y}(i|j), \tag{3.8}$$

$$\mathbf{P}(i|j) = \mathbf{Y}^{-1}(i|j). \tag{3.9}$$

where:

$\mathbf{x}(i\|j)$	-	The state space estimate vector at time index i given the estimates at time index j, e.g. $[x, \dot{x}, y, \dot{y}]^T$.
$\mathbf{P}(i\|j)$	-	The state space covariance matrix at time index i given the estimates at time index j.

It should be noted that the information filter is mathematically equivalent to the Kalman filter. As such it provides the same optimality criteria of maximum likelihood (ML), maximum a posteriori (MAP) and minimum mean square error (MMSE) when all probability distribution functions are Gaussian (Grime et al. 1990)[2].

The information filter is represented in Figure 3.2. Here the target model is used to predict the state, $\hat{\mathbf{Y}}(k|k-1)$ and $\hat{\mathbf{y}}(k|k-1)$, from the previous estimate. In addition, the sensor model converts the sensor reading, $\mathbf{R}(k)$ and $\mathbf{z}(k)$, into sensor information values, $\mathbf{I}(k)$ and $\mathbf{i}(k)$. The predicted and sensor values are combined by the Bayesian based combination algorithm to give an updated estimate of the target's state, $\tilde{\mathbf{Y}}(k|k)$ and $\tilde{\mathbf{y}}(k|k)$.

It should be noted that a potential problem can arise when initialising the filter. This comes about if the filter is required to initialise with complete ignorance about the target's kinematics, i.e. $\mathbf{Y}(0|0)$ set to zero. This can result in implementation problems as $\mathbf{Y}(0|0)$ has to be inverted in the first prediction. However, the *Joseph* form of the prediction equations (Grime 1993) overcomes this:

$$\hat{\mathbf{Y}}(k|k-1) = [\mathbf{I} - \mathcal{X}(k)]\mathcal{U}(k)[\mathbf{I} - \mathcal{X}(k)]^T + \mathcal{X}(k)\mathbf{Q}^{-1}(k)\mathcal{X}^T(k), \tag{3.10}$$

and

$$\hat{\mathbf{y}}(k|k-1) = [\mathbf{I} - \mathcal{X}(k)]\mathbf{F}^{-1T}(k)\tilde{\mathbf{y}}(k-1|k-1), \tag{3.11}$$

[2]In practice this may not be the case, but the Kalman filter will still produce the Best Linear Unbiased Estimate (BLUE).

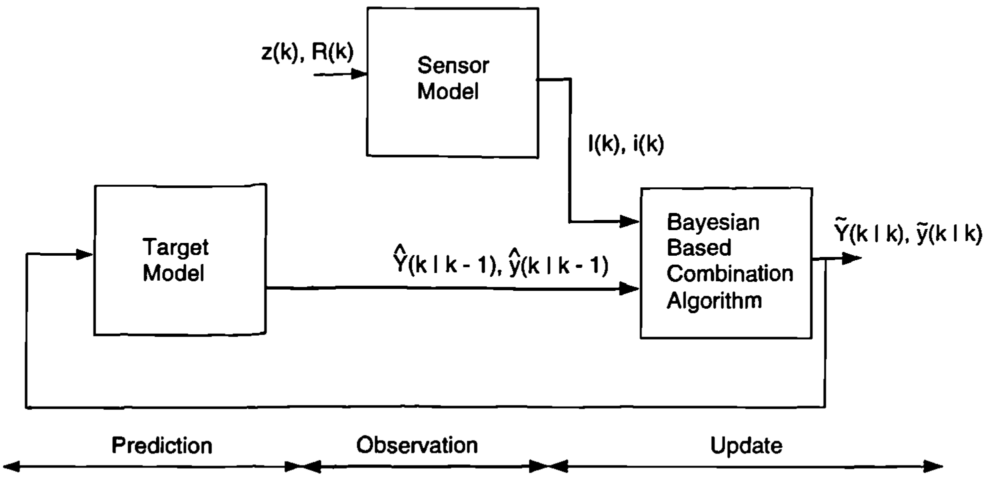


Figure 3.2: Prediction-observation-update cycle of a recursive kinematic estimation algorithm.

where

$$\mathcal{U}(k) = \mathbf{F}^{-1T}(k)\tilde{\mathbf{Y}}(k-1|k-1)\mathbf{F}^{-1}(k), \tag{3.12}$$

and

$$\mathcal{X}(k) = \mathcal{U}(k)[\mathcal{U}(k) + \mathbf{Q}^{-1}(k)]^{-1}. \tag{3.13}$$

Note that complete initialisation ignorance is represented by setting $\tilde{\mathbf{Y}}(0|0)$ with zeros. Here this value is not inverted. The drawback with this form of the prediction equations is that matrix inversion problems are encountered when predicting forward by zero time period, i.e. $\mathbf{Q}(k)$ set to zeros.

A computational analysis of the information filter and Kalman filter was carried-out in (Grime 1993). This indicates that:

- the prediction stage of the information filter is more computationally expensive than for the Kalman filter, and
- the update stage of the Kalman filter is more computationally expensive than for the information filter.

Therefore, since (generally) multi-sensor systems use a single prediction and multiple updates, the information filter potentially provides a more computationally efficient solution.

3.3.2 An Identification Estimator

Various methods and algorithms exist for combining multiple target estimates. These include Dempster-Shafer evidential reasoning, artificial neural networks, and voting methods (Klein 1993). This section describes a Bayesian based recursive identification algorithm. Further this algorithm is developed to an *information form.*

Let an identity estimate vector for a *mutually exclusive and exhaustive* set of distinct object types be:

$$\mathbf{X} = \{X_1, X_2, \ldots\}, \tag{3.14}$$

and having made k independent observations the posterior distribution is given from Bayes theorem, see Equation 3.6:

$$P(\mathbf{X}|\mathbf{Z}^k) = P(\mathbf{X}|\mathbf{Z}^{k-1}) \times P(Z(k)|\mathbf{X}) \times \alpha_k, \tag{3.15}$$

where $Z(k)$ is an observation which contains a characteristic(s) of the target's identity. $P(Z(k)|\mathbf{X})$ is referred to as the 'likelihood', i.e. the probability of obtaining the observation, $Z(k)$, given the object set $\mathbf{X}$.

This algorithm can be transformed into the information state by taking logarithms to the base e of Equation 3.15. This gives:

$$\ln[P(\mathbf{X}|\mathbf{Z}^k)] = \ln[P(\mathbf{X}|\mathbf{Z}^{k-1})] + \ln[\alpha_k \times P(Z(k)|\mathbf{X})]. \tag{3.16}$$

This has analogy to the kinematic update, see Table 3.1, and can be represented as:

$$\mathcal{Y}(k) = \mathcal{Y}(k-1) + \mathcal{I}(k), \tag{3.17}$$

Equations 3.15 to 3.17 form the target identification algorithm used for this thesis.

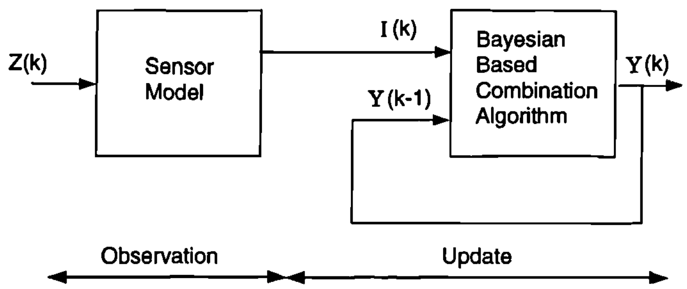


Figure 3.3: Observation-update cycle of a recursive identification algorithm.

To summarise, the observation-update cycle of the recursive identification algorithm is represented in Figure 3.3. Here an observation, e.g. $Z(k)$, is input to the recursive identification algorithm which results in an identity estimate vector being produced, e.g.:

$$\begin{array}{cc} \text{Fighter} & \text{Bomber} \\ \{0.2 & 0.8\} \end{array} \tag{3.18}$$

This is achieved by transforming the reading, $Z(k)$, to the likelihood information, $\mathcal{I}(k)$, by the sensor model. This is the observation stage of the identification algorithm cycle. The likelihood information along with the prior identity information, $\mathcal{Y}(k-1)$, are combined to give the posterior identity information, $\mathcal{Y}(k)$. This is referred to as the update stage of the identification algorithm cycle.

This section has answered the question 'what are the basic Bayesian kinematic and identity estimators used for this thesis?' The kinematic algorithm is the information filter. Two different formulations were provided, one based on the conventional prediction equations the other based on the Joseph form. These provide slightly different operating abilities based on dealing with a zero valued information state covariance matrix or process noise covariance. The information filter is mathematically equivalent to the more popular Kalman filter but, in full generality, is less computationally expensive for decentralised applications. Further, the simple identification algorithm is also stated in its information form.

3.4 Decentralised Data Fusion Algorithms

This section leads on from the previous and aims to answer the following question 'what is the formulation of these algorithms for decentralised systems?' This is achieved by providing details of the decentralisation of both the kinematic and identification algorithms.

3.4.1 The Decentralised Information Filter

Here the single sensor and single target information filter is developed for a multi-sensor application based on fully decentralised and fully connected system with an ideal[3] communications mechanism. This is represented in Figure 3.4. Here the predict-observe-update cycle of the filter is developed to include an additional communication step. Hence the cycle comprises predict-observe-communicate-update stages. Each node of the decentralised system has an information filter modified in this way, see Figure 3.4.

[3]Zero latency, infinite bandwidth.

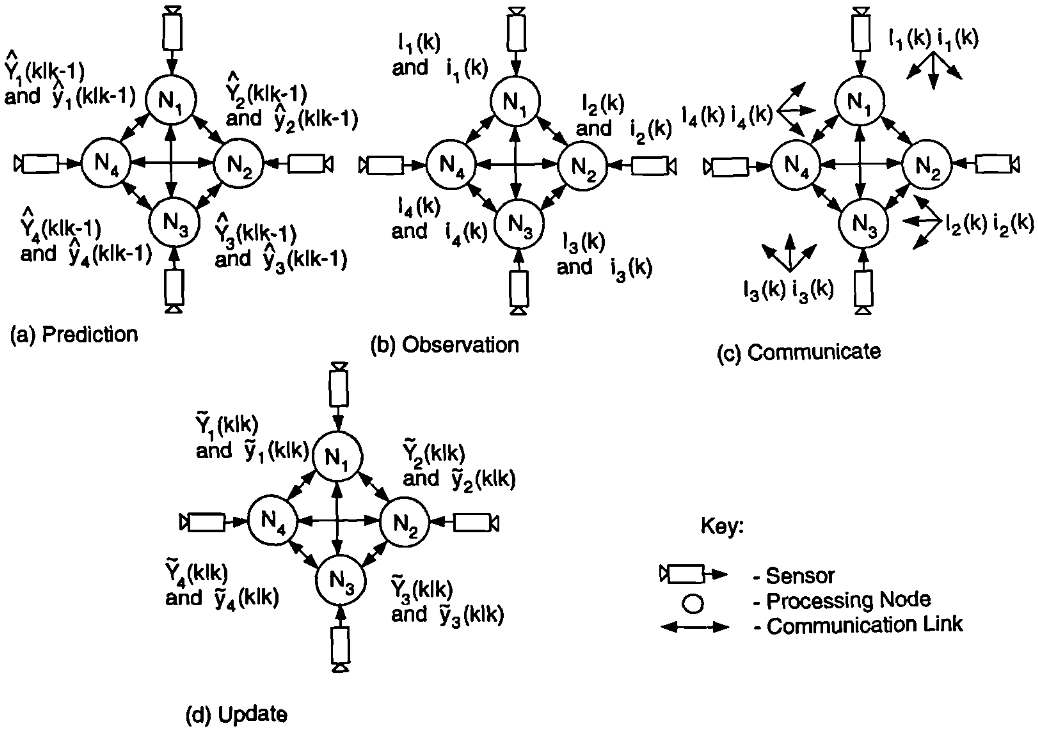


Figure 3.4: A synchronised, fully connected, decentralised kinematic estimation system with 'ideal' communications.

These filters are **predicted** synchronously, see Figure 3.4(a), using Equations 3.19 and 3.20:

$$\hat{\mathbf{Y}}_i(k|k-1) = [\mathbf{F}(k)\tilde{\mathbf{Y}}_i^{-1}(k-1|k-1)\mathbf{F}^T(k) + \mathbf{Q}(k)]^{-1}, \tag{3.19}$$

$$\hat{\mathbf{y}}_i(k|k-1) = \hat{\mathbf{Y}}_i(k|k-1)\mathbf{F}(k)\tilde{\mathbf{Y}}_i^{-1}(k-1|k-1)\tilde{\mathbf{y}}_i(k-1|k-1). \tag{3.20}$$

where i is an index of the nodes in the network.

The **observation** values, $\mathbf{z}_i(k)$ and $\mathbf{R}_i(k)$, are converted to the information form, see Figure 3.4(b), using Equations 3.21 and 3.22:

$$\mathbf{i}_i(k) = \mathbf{H}_i^T(k)\mathbf{R}_i^{-1}(k)\mathbf{z}_i(k), \tag{3.21}$$

$$\mathbf{I}_i(k) = \mathbf{H}_i^T(k)\mathbf{R}_i^{-1}(k)\mathbf{H}_i(k). \tag{3.22}$$

During the **communication** stage the processed observations, i.e. $\mathbf{i}_i(k)$ and $\mathbf{I}_i(k)$, are communicated to all other nodes in the system, see Figure 3.4(c). In addition, all other processed observations are received from the other nodes. These communications are carried-out synchronously.

The **update** stage of the filter combines all the observation values of the system with the predicted values, see Figure 3.4(d), using Equations 3.23 and 3.24. Therefore $\forall i$:

$$\tilde{\mathbf{y}}_i(k|k) = \hat{\mathbf{y}}_i(k|k-1) + \sum_{\forall j} \mathbf{i}_j(k), \tag{3.23}$$

$$\tilde{\mathbf{Y}}_i(k|k) = \hat{\mathbf{Y}}_i(k|k-1) + \sum_{\forall j} \mathbf{I}_j(k). \tag{3.24}$$

where j is an index of the nodes in the network. At the end of the update stage each of the nodes have identical estimates.

The transition from a single target to a multiple target implementation is straight forward and achieved by employing a 'bank' of information filters, one for each target. In this dissertation the prefix, t, is employed to index the target being considered. For example, the kinematic update equations for a multi-target implementation become:

$${}^t\tilde{\mathbf{y}}_i(k|k) = {}^t\hat{\mathbf{y}}_i(k|k-1) + \sum_{\forall j} {}^t\mathbf{i}_j(k), \tag{3.25}$$

$${}^t\tilde{\mathbf{Y}}_i(k|k) = {}^t\hat{\mathbf{Y}}_i(k|k-1) + \sum_{\forall j} {}^t\mathbf{I}_j(k). \tag{3.26}$$

Further, the assignment of observations to kinematic estimators is referred to as *data association*[4]. In addition, when data association is combined with the kinematic estimator the process is referred to as *tracking.*

It should be noted that for a distributed system, the values of $\mathbf{I}(k)$ and $\mathbf{i}(k)$ would be calculated at the distributed nodes. These would then be communicated to a central processor which would carry-out the assimilation of all data. In order for the distributed nodes to obtain an equivalent decentralised estimate the central information estimate, $\tilde{\mathbf{y}}(k|k)$, and its associated information covariance, $\tilde{\mathbf{Y}}(k|k)$, would then be communicated back to the distributed processing nodes.

3.4.2 The Decentralised Identification Algorithm

Here the single target and single sensor identification algorithm is developed for use on a multi-sensor decentralised system. Figure 3.5 represents a synchronised, fully connected, fully decentralised identification system with an ideal communications mechanism. As before the observation-update cycle is developed to include an additional communication step. Each node of the decentralised system has its own identification estimator, see Figure 3.5.

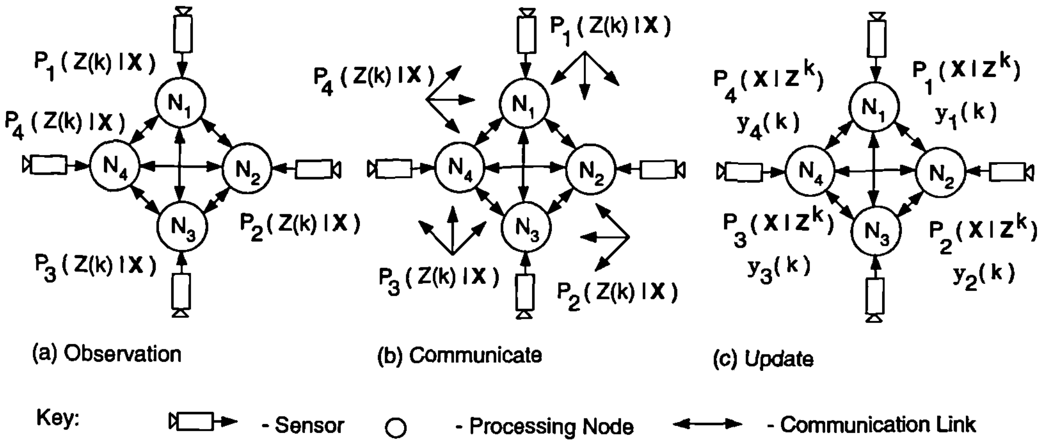


Figure 3.5: A synchronised, fully connected, decentralised identification system with 'ideal' communications.

The **observation** stage comprises taking the reading $Z_i(k)$ and obtaining a likelihood, $P_i(Z(k)|\mathbf{X})$[5].

[4]Data association is also concerned with track initiation and reaping (Blackman 1986).

[5]It should be noted that the sub-script i is omitted from the $Z(k)$ since it is implicit in P_i.

The **communication** step of the target identification estimator, see Figure 3.5(a), results in the synchronised communication of a nodes observation likelihood, $P_i(Z(k)|\mathbf{X})$, to all other nodes in the system. In addition, the observation likelihood from all other nodes is received synchronously.

When the communication is complete the identification estimator is **updated**, see Figure 3.5(b), using Equation 3.27 and the corresponding *Equation* 3.28. Therefore, $\forall i$:

$$P_i(\mathbf{X}|\mathbf{Z}^k) = P_i(\mathbf{X}|\mathbf{Z}^{k-1}) \times \prod_{\forall j} P_j(z(k)|\mathbf{X}) \times \alpha_j \tag{3.27}$$

$$\mathcal{Y}_i(k) = \mathcal{Y}_i(k-1) + \sum_{\forall j} \mathcal{I}_j(k). \tag{3.28}$$

It should be noted that the observation likelihood has to be communicated and not its information form. This situation arises since α_j is a function of the prior and the likelihood.

As for the information filter, the transition from a single target to a multiple target implementation is straight forward and achieved by employing a 'bank' of identification estimators, one for each target. As before, the prefix, t, is employed to index the target being considered. For example, the equations for a multi-target implementation become[6]:

$$^tP_i(\mathbf{X}|\mathbf{Z}^k) = {}^tP_i(\mathbf{X}|\mathbf{Z}^{k-1}) \times \prod_{\forall j} {}^tP_j(Z(k)|\mathbf{X}) \times {}^tC_j \tag{3.29}$$

This section has answered the question 'what is the formulation of these algorithms for decentralised systems?' This has been achieved by developing the kinematic and identity estimation algorithms of the previous section to that of a multi-sensor and multi-target scenario. This development is based on implementing a fully decentralised and fully connected system employing an ideal communication system.

3.5 The Connectivity of Decentralised Systems

This section of the chapter aims to answer the question 'what connectivity will be employed for the decentralised system of this thesis?' This is achieved by considering the motivation for topologies of different connectivity, comparing their advantages and disadvantages and considering the logical and physical implementation.

[6]The prefix t on $P(\cdot)$ implies $^t\mathbf{Z}$ and $^tZ(k)$ and is therefore not shown explicitly.

3.5.1 Motivation

The practical implementation of decentralised systems may have technical restrictions. For example, the available number of communication links that can be employed, e.g. in (Grime et al. 1990) transputers were employed which restricted the number of available (physical) communication links to 4. Such a constraint restricts the maximum size of the system and has resulted in the investigation of non-fully connected systems.

Further, the communications bandwidth of a link may also be restricted, e.g. due to the available hardware. This results in a non-ideal communications system. To date, in decentralised systems (Grime et al. 1990) this problem has been addressed by assimilating data to be transmitted on a link.

These techniques are discussed further below.

3.5.2 Fully and Non-Fully Connected Systems

There are many advantages and disadvantages to employing non-fully connected topologies in decentralised systems. Some of these are discussed below:

Number of Links

One of the major advantages of a non-fully connected decentralised system is that it employs fewer communication links. For a fully connected topology, consisting of N nodes, the number of communication links required is given by L_f, as:

$$L_f = N.(N-1). \tag{3.30}$$

The minimum number of links required for a non-fully connected network is given by L_n, as:

$$L_n = 2.(N-1). \tag{3.31}$$

However, given the constraint that non-fully connected decentralised systems have to be *loop free* (Utete and Durrant-Whyte 1994b), to avoid double data counts, the number of links must be equal to L_n.

This loopless constraint arises since the decentralised philosophy expects each node to have only local knowledge of the network. This is best explained by an example. Consider a four node system shown in Figure 3.6. Here node $N1$ makes and observation and communicates the associated information, I, to nodes $N2$ and $N3$. These nodes in-turn propagate their information on to node $N4$. Therefore, the loop in the system has resulted in $N4$ receiving this information twice. Several methods exist to overcome this problem, see primarily (Utete 1994). However, these methods either relax the decentralised philosophy, e.g. by employing a knowledge of the complete network, or result in sub-optimal systems, e.g. by assuming all the communicated data is correlated.

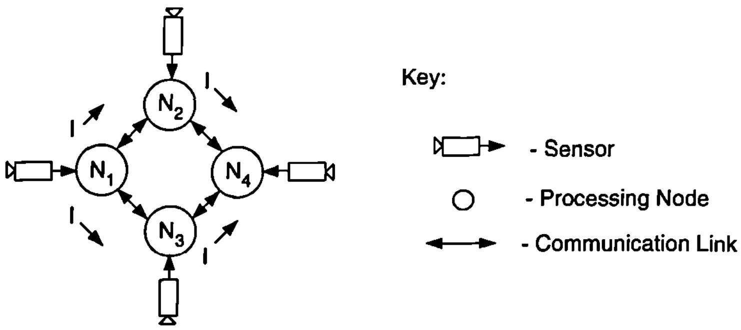


Figure 3.6: Double data counts in topologies incorporating loops.

Hence, for large networks, i.e. $N \gg 1$, a considerable saving in the number of communication links required can be made by employing the non-fully connected topology, i.e. $L_n \ll L_f$.

In non-fully connected decentralised systems, data may be assimilated prior to communication. This is achieved by employing a *channel filter* and results in the advantage of a reduced communications bandwidth requirement when compared with a fully connected system.

The role of this channel filter is to maintain a record of all information that has been communicated through that link, transmitted and received. The channel filter, along with the nodes global estimator, can then be used to calculate *new* information that needs to be transmitted down that channel. This is achieved by *subtracting* the channel filter information from the global filter information.

The functionality of the channel filter is represented in Figure 3.7. Here a three node system, $N1$, $N2$ and $N3$ employ a line topology. Below each node is an *information map.* These provide clarity on (Grime 1993) and are extended here with labelled items of data. A similar approach based on *information graphs* is presented in (Chong et al. 1992). The y axis represents the data assimilated at that node at a time represented on the x axis. Data is introduced to the system via the sensors. These data are represented by the notation, Ni, k, which indicates that the datum was generated from node i at time index k. Figure 3.7 shows the introduction of several synchronous sensor readings at times $T1$ and $T2$. The data generated from the readings are used to update the global filters. After an inter-nodal communication the channel filters are updated. When the observations

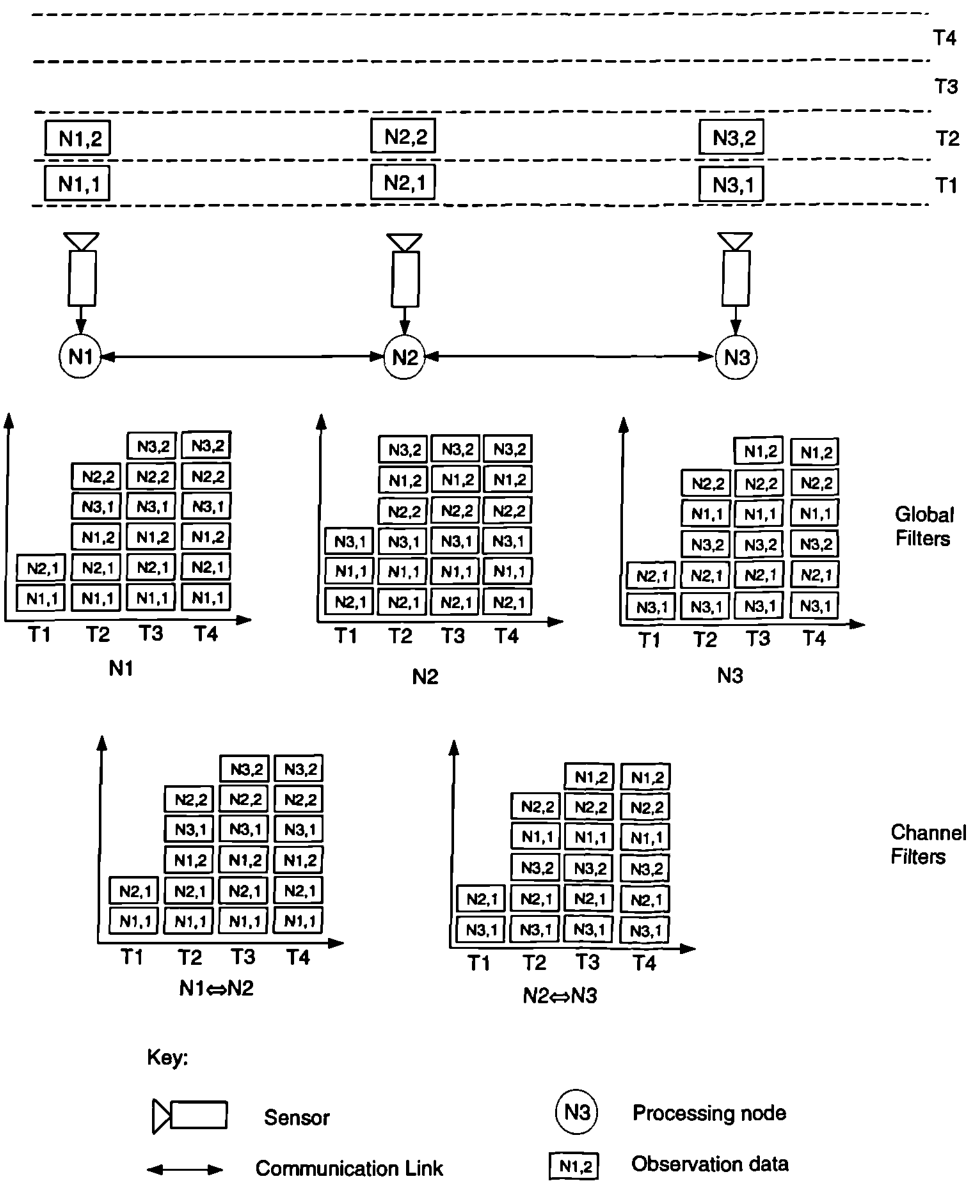


Figure 3.7: The channel filter in non-fully connected decentralised topologies, see the text for a description of this diagram.

stop, and all the data have propagated, all the nodes have the same information, e.g. at time $T4$ in Figure 3.7.

It should be noted that a channel filter need *only* be maintained at one end of the communication link. However, this can result in asymmetric topologies. In addition, such implementations remove the extensibility properties of decentralised systems. Therefore these are not generally recommended and their use should only be applied after a detailed behavioural investigation of the system and its specification.

Bandwidth Requirements

The bandwidth requirements of non-fully connected systems are now considered. In Figure 3.8(a) the communications that take place when all three nodes make an observation are represented. The equivalent fully connected system is represented in (b). Here the non-fully connected (line) system makes $2.(N-1)$ communications, i.e. 4 in the example, while the fully connected system makes $N.(N-1)$ communications, i.e. 6 in the example.

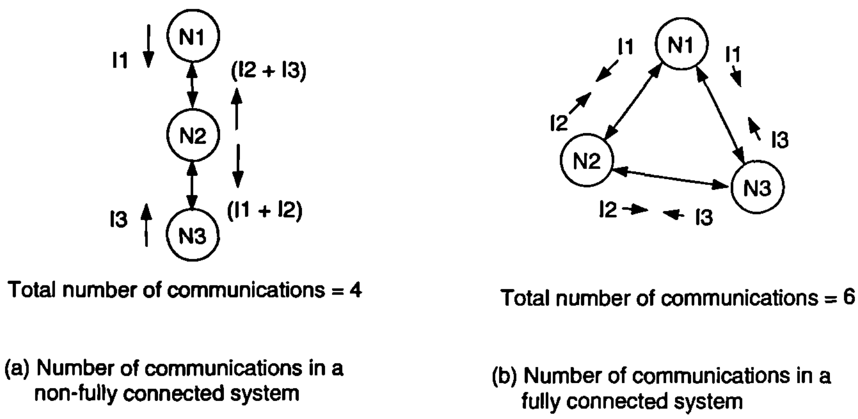


Figure 3.8: Non-fully and fully connected system bandwidth requirements.

Hence, for large networks a considerable saving in the required communication bandwidth can be made by employing the non-fully connected topology.

Disadvantages

The major disadvantages of non-fully connected systems are that the processing nodes have to support an additional computational cost and that the system is subject to propagation delays. The additional computation is brought about since a processing node has to maintain a *channel filter* on each communication link. The transient delay is best explained by an example: Consider a simple three node system as shown in Figure 3.9.

The fully connected topology is represented by schematic (a) while the partially linked implementation is represented in diagram (b). If node $N1$ makes an observation in (a) this information is communicated to all the other nodes, $N1$ and $N2$, during the next communication. This is not the case for the non-fully connected implementation. If node $N'1$ makes an observation in (b) it will be communicated to $N'2$ during the next communication. However, this information does not reach $N'3$ until the *next* communication. Therefore, node $N'3$ has experienced a propagation delay in receiving information from node $N'1$.

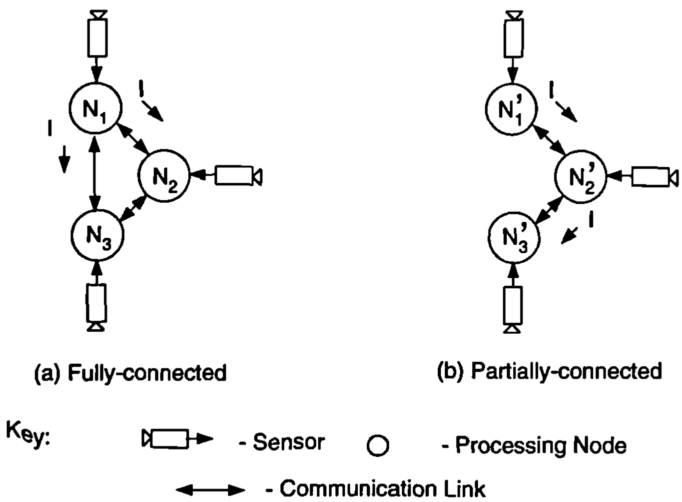


Figure 3.9: Data latency in decentralised topologies.

3.5.3 Logical and Physical Implementations

For large complex systems such as those employed by the military, e.g. the Battlefield Awareness and Data Dissemination (BADD) (Newsome et al. 1998) system, physical communication loops will exist (Marquet and Ratches 1998) between different sensing nodes. Further, the physical topology of the system will be evolving with time and scenario. Therefore, in order to maintain the bandwidth reduction benefits of non-fully connected topologies the logical implementation will also need to evolve to match the physical implementation. This poses two problems for non-fully connected decentralised implementations:

If the non-fully connected logical implementation is not matched to the non-fully connected physical implementation the benefits of reduced communications bandwidth requirement diminishes (this is an area of on-going research). Figure 3.10 represents this problem. Diagram (a) provides the logical implementation for a non-fully connected system. The mapping of this implementation onto a matched physical implementation is represented in (b). Further the four inter-nodal communications are also shown. The effect of a mis-matched physical implementation is represented in (c). Here two additional communications are required, i.e. the relaying of $I3$ from node $N1$ to $N2$ and $(I1 + I2)$ from node $N1$ to $N3$. This simple example indicates that the total number of communications has increased.

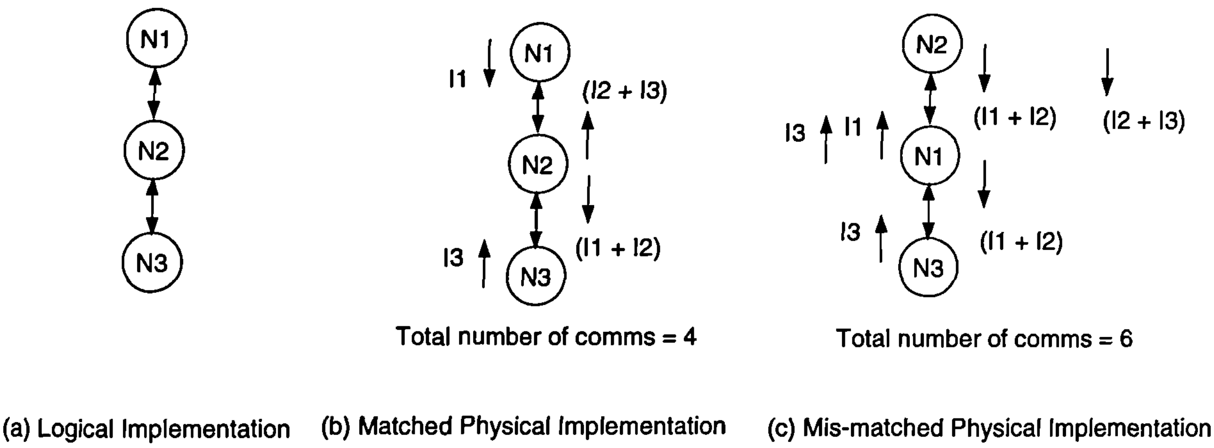


Figure 3.10: The effect of mis-matched logical and physical implementations.

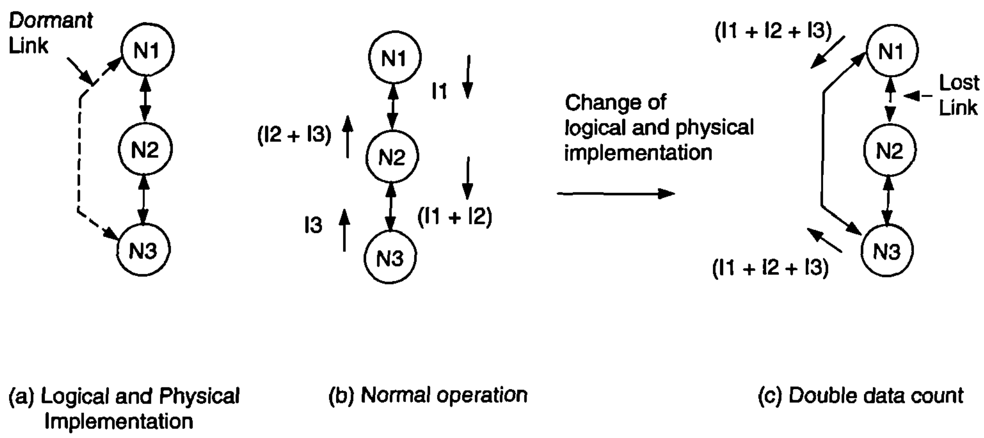


Figure 3.11: Double data counts in systems with evolving connectivity.

In order to overcome the problem associated with a mis-matched and evolving physical implementations the logical implementation be should adaptable. This can result in an additional communications overhead required for re-arranging the logical implementation. This adaptability can result in double data counts (Utete and Durrant-Whyte 1994b).

Consider the situation represented in Figure 3.11. The physical implementation is represented in (a). Here a dormant link is employed to increase the systems survivability to the (temporary) loss of a communication link. Normal operation is shown in (b). The communication link between nodes $N1$ and $N2$ is lost in (c). In order, to maintain connectivity the dormant link between nodes $N1$ and $N3$ is activated. This changes both the logical and physical implementation of the system. In this situation both $N1$ and $N3$ suffer from double data counts. This example shows that although the physical and logical implementation of the system has not, at any time, contained loops the change from one connectivity to another has introduced the problem of double data counting. Further details of connectivity problems in decentralised systems are provided in (Utete and Durrant-Whyte 1994b).

These problems, which are currently being researched, motivate the use of a logically fully connected decentralised system for this thesis.

This section has answered the question 'what connectivity will be employed for the decentralised system of this thesis?' This was achieved by considering the motivations for non-fully connected topologies. Such systems provide two benefits: (i) a reduction in the number of communication links required, and (ii) a reduction in the system bandwidth required. However, in order to avoid double data counts the logical implementation of these systems must be loop free. Networks, particularly military systems, will employ evolving physical systems. Such systems reduce the benefit of logically non-fully connected systems if they are not matched to the physical implementation. In addition, if an adaptable non-fully connected system is employed to match the evolving physical implementation double data count problems can be encountered even though no logical or physical loops have existed at any time. These arise due to the connectivity evolving. Solutions to these problems are on-going research areas at other institutions, e.g. Utete at Oxford University. Hence, in order to avoid these problems the use of a logically fully connected decentralised system is motivated for this thesis.

3.6 The Channel Filter

This section of the dissertation aims to answer the question 'what is the role of the channel filter for a bandwidth limited communication link?'

3.6.1 Previous Implementation: Non-fully Connected Systems

As discussed in the previous section the use of channel filters has been successfully applied to non-fully connected decentralised systems. This was first introduced in the work of (Grime 1993) and has also been applied in the research work of (Ho 1994) and (Utete and Durrant-Whyte 1994b).

Therefore, since the channel filter concept has been applied in a number of research projects its application for this thesis is favoured.

3.6.2 Proposed Implementation: Bandwidth Limited Systems

In (Grime 1993) (page 85) it was briefly mentioned that it would be possible to apply the channel filter in single target, bandwidth constrained systems. However, no implementation details or investigation results for such an application were provided.

A description of how to apply the channel filter in single target bandwidth constrained systems is provided next: Consider the two node system represented in Figure 3.12. Here the inter-platform bandwidth is constrained such that each node communicates in turn after two sensor updates. The first communication is from node $N2$ to node $N1$ at time $T2$. Here an assimilation version of data $N2,1$ and $N2,2$ is communicated to node $N1$. This assimilation is provided by a Bayesian based combination algorithm for this thesis. This communication updates the channel filter and the global filter of node $N1$. At time $T4$ node $N1$ communicates assimilated data $N1,1$ and $N1,2$ to node $N2$. This communication updates the channel filter and the global filter of node $N2$.

In summary, the channel filter can be applied to single target bandwidth constrained systems. This is achieved by introducing a latency to the communicated data.

> This section has answered the question 'what is the role of the channel filter for a bandwidth limited communication link?' This was achieved by referencing the channel filters previous applications and describing its use for single target bandwidth constrained systems. A more detailed implementation description is provided in Chapter 5. The fact that the channel filter has been applied in the research of other projects adds weight to its implementation in this thesis.
> The research of this dissertation is concerned with developing the application of a channel filter as described by (Grime 1993) for a multi-target implementation.

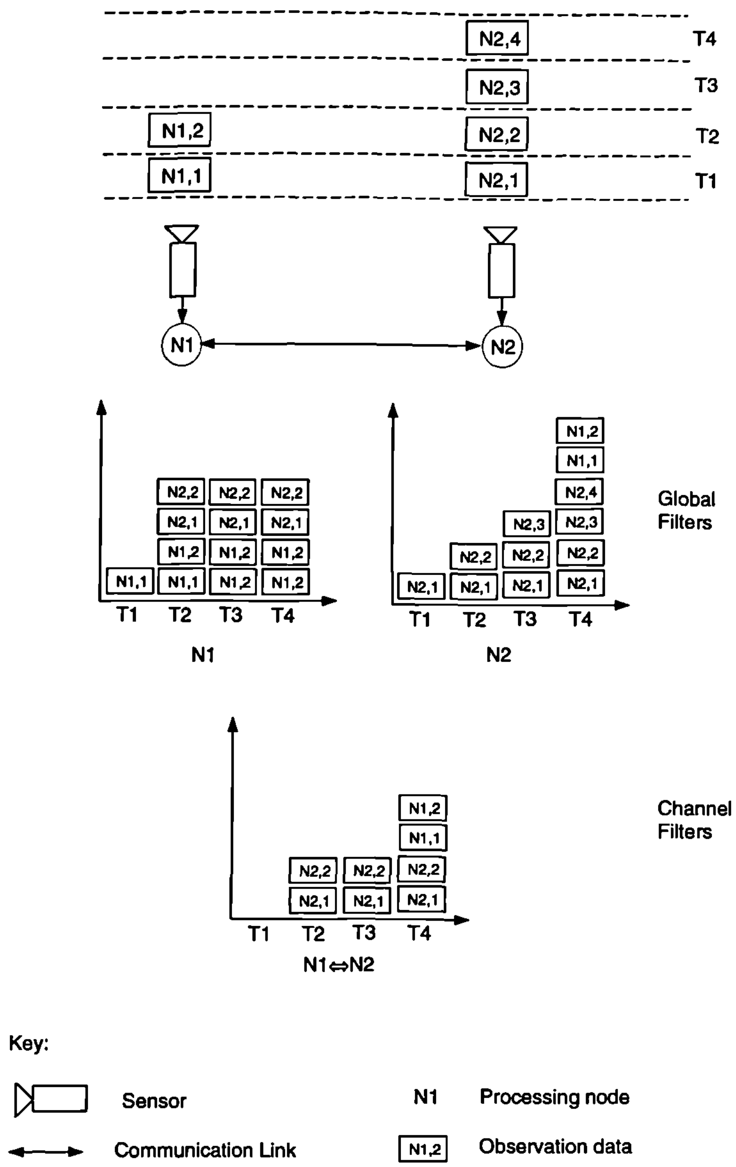


Figure 3.12: The channel filter in reduced bandwidth decentralised systems, see the text for a description.

3.7 Summary and Concluding Remarks

This chapter began by stating a number of questions derived from 'what are the data fusion algorithms used in this thesis?' These have been answered in the sections of the chapter. Here these are used to answer the following question 'why are they being employed?'

- *'Why the information filter?'*
  The Bayesian based information filter is being employed as a kinematic estimator for this thesis. This choice is based primarily on two facts: (i) the information filter is, generally, computationally less expensive than the more popular Kalman filter for decentralised systems, and (ii) the information filter has been applied successfully in a number of research projects based on decentralised systems.

- *'Why the identity estimator?'*
  A Bayesian based identification estimator is being employed for this thesis. This is based on two facts: (i) the Bayesian identity estimator is easy to employ and code, and (ii) it has been used successfully in a number of decentralised systems research projects.

- *'Why employ a fully connected topology?'*
  The application area for this thesis is focussed on future avionic systems. These systems will employ communication systems whose connectivity will change with a dependence on the scenario. A number of research questions remain un-answered concerning logically adaptive non-fully connected systems. These include: (i) the performance of non-fully connected systems when the logical and physical implementations are mis-matched, and (ii) the double data count problems that occur when the physical implementation is evolving and an adaptive logical implementation is changing to match the evolving system. These problems do not occur for fully connected systems. As such, their use for this thesis is motivated.

- *'Why the channel filter?'*
  The channel filter has been successfully applied within a number of decentralised systems research projects. Further, it has been suggested that the channel filter can be applied in single target system with inter-nodal communication links experiencing a reduced bandwidth. This application area has been investigated by example in this chapter. These facts motivate the use of the channel filter for this thesis.

The answers to these questions provide the infrastructure capabilities for this thesis. These are now stated:

Data fusion algorithms for multi-sensor, multi-target and fully connected decentralised systems have been provided. These are based on two Bayesian estimation algorithms: (i) a kinematic estimator, i.e. the information filter, and (ii) an identity estimator. Further, the ability of the channel filter for dealing with a reduced inter-nodal communications bandwidth in single target systems has been investigated and deemed suitable.

Chapter 4

Information Based Decision Theory

4.1 Introduction

> The aims of this chapter are to answer the questions '*what* are the information metrics and decision techniques used in this thesis?' and '*why* are they being employed?' These answers provide the management capabilities of the thesis.

The mapping between these questions and sections of the chapter are provided in Figure 4.1. Details of information metrics for target kinematics and identification are provided in Section 4.2. Their use in data fusion systems are discussed in Section 4.3. Information gains based on relative and absolute information are considered in Section 4.4. Decision theory techniques and their application to the work of this dissertation are discussed in Section 4.5. A summary and concluding remarks of the chapter are provided in Section 4.6. These lead to a statement of the management capabilities of the thesis. The *what* question is answered in Sections 4.2 to 4.5, the *why* question in Section 4.6.

4.2 Information Metrics

This section of the chapter aims to answer the question 'what information metrics are suitable for data fusion?' This is achieved by stating a number of different information metrics for kinematic and identity estimators. This is followed by a discussion of the merits of *entropic* information.

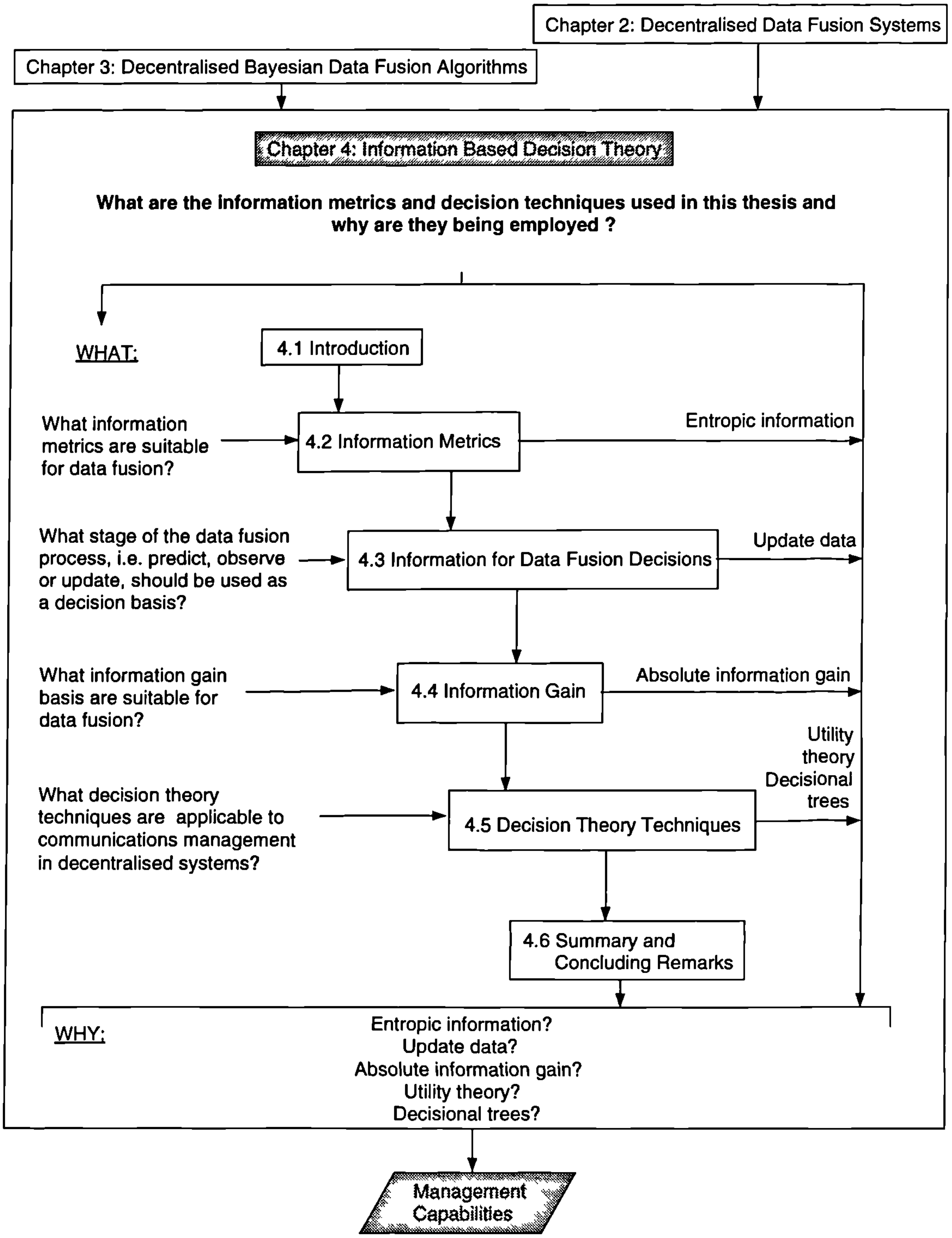


Figure 4.1: Reader's map for Chapter 4.

4.2.1 Information Metrics for (Continuous) Kinematic Data

From the derivations in Chapter 3 a target's kinematic estimation is dependent on three vectors and their associated covariance matrixes. These are:

1. *Prediction*, i.e. $\tilde{\mathbf{x}}(k|k-1)$ and $\tilde{\mathbf{P}}(k|k-1)$,

2. *Observation*, i.e. $\mathbf{z}(k)$ and $\mathbf{R}(k)$, and

3. *Update*, i.e. $\hat{\mathbf{x}}(k|k)$ and $\hat{\mathbf{P}}(k|k)$.

Information values can be calculated for each of the above. Therefore, for the remainder of this section we shall consider the kinematic data of the general vector $\mathbf{x}$ and its associated covariance $\mathbf{P}$.

Further, it is assumed that the distribution of $\mathbf{x}$ is Gaussian of state dimension l. This is represented as:

$$p(\mathbf{x}) = (2\pi)^{-l/2}|\mathbf{P}|\exp\left[-\frac{1}{2}(\mathbf{x}-\bar{\mathbf{x}})^T\mathbf{P}^{-1}(\mathbf{x}-\bar{\mathbf{x}})\right], \tag{4.1}$$

where $\bar{\mathbf{x}}$ is the mean of the distribution. Some possible kinematic information metrics are now discussed:

1. **Fisher information:** This is defined as the negative expectation of the Hessian of the kinematic distribution (Bar-Shalom and Li 1993):

$$\mathbf{J}(k) = -E\{\Delta_{\mathbf{x}}\Delta_{\mathbf{x}}^T\ln(p(\mathbf{x}))\}. \tag{4.2}$$

   This is an useful metric in estimation when the 'likelihood' (based on the observation or sensor model) is employed since inverted it provides the *Cramer-Rao lower bound* (Bar-Shalom and Fortmann 1988) which bounds the mean-squared error of any unbiased estimator of $\mathbf{x}$.

2. **Entropic information:** This is defined as $h(\mathbf{x}) = -E\{\ln(p(\mathbf{x}))\}$, where E is the expectation. (Manyika and Durrant-Whyte 1994) provide the following derivation:

$$h(\mathbf{x}) = -\frac{1}{2}\ln[(2\pi e)^l|\mathbf{P}|]. \tag{4.3}$$

These definitions are used according to the particular application.

4.2.2 Information Metrics for (Discrete) Identification Data

From the derivations in Chapter 3 a targets identification is dependent on three vectors. These are:

1. *Previous Estimate*, i.e. $P(\mathbf{X}|\mathbf{Z}^{k-1})$,
2. *Observation*, i.e. $P(Z(k)|\mathbf{X})$, and
3. *Update*, i.e. $P(\mathbf{X}|\mathbf{Z}^{k})$.

Information values can be calculated for each of the above. Therefore, for clarity we shall consider the target identification information of the general probability vector $P(\mathbf{X})$.

A number of simple information definitions exist for target identification. These include (Cover and Thomas 1991):

1. **Elemental information:** This is defined as:

$$I_e = \ln(P(X)) \tag{4.4}$$

2. **Vector information:** This is defined as:

$$I_v = \sum_{\forall X \in \mathbf{X}} \ln(P(X)) \tag{4.5}$$

3. **Average or entropic information** This is defined as:

$$H(\mathbf{X}) = \sum_{\forall X \in \mathbf{X}} P(X)\ln(P(X)) \tag{4.6}$$

These definitions are used according to the particular application.

4.2.3 The Merits of Entropic Information

Entropic information is a very intuitive metric. Here the maximum value is obtained when *absolute certainty* of an event is achieved. Conversely, the minimum entropic information is obtained when *absolute uncertainty* of an event is achieved. Other merits of this information metric include its ability to be applied to discrete and continuous distributions. Further, since entropic information provides a scalar value it is a suitable representation for decision making . In addition, it has already been successfully applied to decentralised data fusion sensor management (Manyika and Durrant-Whyte 1994). It should be noted that the general information forms of the kinematic and identification estimators, as described in Section 3.3, can easily be re-formulated in the entropic information form.

The aim of this section was to answer the question '*what* information metrics are suitable for data fusion?' A number of *information* definitions have been stated that are suitable for kinematic and identification data. These are used according to the particular application. Further, a number of advantages have been documented that highlight entropic information as a suitable metric for the work presented in this dissertation.

4.3 Information for Data Fusion Decisions

This section aims to answer the question 'what stage of the data fusion process, i.e. predict, observe or update, should be used as a decision basis?' This question arises since it is intuitive to assume that the update entropic information will be the sum of the predicted entropic information and the observed entropic information. This leads to the assumption that maximising the observation entropic information also maximises the update entropic information. However, this assumption does *not* always hold true due to the effect of *mutual entropic information.* This issue is discussed in this section with worked data fusion examples.

4.3.1 Mutual Information

Here the concept of mutual information (Cover and Thomas 1991) and its effect on combining data is considered. An illustrative example of data combination is represented in Figure 4.2. Here the predicted or previous update entropic information, I_{pr}, is enhanced by the observation entropic information, I_{ob}, to provide the update entropic information, I_{up}. However, the relationship between these values is not purely additive since an element of mutual entropic information, I_{mu}, will exist between I_{pr} and I_{ob}. Therefore:

$$I_{up} = I_{pr} + I_{ob} - I_{mu} \tag{4.7}$$

This representation is further investigated below by way of worked examples.

4.3.2 Kinematic Information

Here a kinematic estimator example is provided. Let the predicted information state covariance of the estimator be represented by the following matrix:

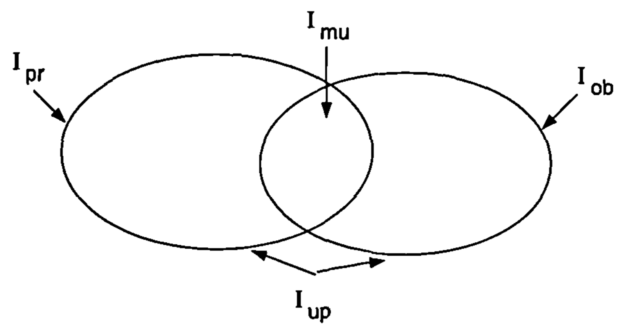


Figure 4.2: Mutual information in data fusion.

$$\mathbf{Y}(k|k-1) = \begin{bmatrix} 0.7 & 0 \\ 0 & 0.2 \end{bmatrix} \tag{4.8}$$

and the observation information state covariance matrix by:

$$\mathbf{I}(k) = \begin{bmatrix} 0.1 & 0 \\ 0 & 0.5 \end{bmatrix}. \tag{4.9}$$

The combination of these values using the information filter, see Section 3.3, provides the updated estimate as:

$$\mathbf{Y}(k|k) = \begin{bmatrix} 0.8 & 0 \\ 0 & 0.7 \end{bmatrix}. \tag{4.10}$$

However, this is *not* equivalent to the addition of the *entropic information*, i.e. using Equation 4.3:

$$h(\mathbf{Y}(k|k)) \neq h(\mathbf{Y}(k|k-1)) + h(\mathbf{I}(k)) \tag{4.11}$$

or

$$(-3.13) \neq (-3.82) + (-4.34). \tag{4.12}$$

This situation arises since the mutual entropic information has not been taken into account. For this example its value can be calculated as:

$$h(I_{mu}(k)) = h(\mathbf{Y}(k|k-1)) + h(\mathbf{I}(k)) - h(\mathbf{Y}(k|k)) \tag{4.13}$$

or

$$h(I_{mu}(k)) = (-3.82) + (-4.34) - (-3.13) = -5.03. \quad (4.14)$$

Further, if the entropic information content of the observation is *increased* by using $\mathbf{I}^{\star}(k)$:

$$\mathbf{I}^{\star}(k) = \begin{bmatrix} 0.6 & 0 \\ 0 & 0.1 \end{bmatrix} \quad (4.15)$$

that is $h(\mathbf{I}^{\star}(k)) = -4.24$. The corresponding update entropic information *reduces*, i.e. $h(\mathbf{Y}^{\star}(k|k)) = -3.39$. This counter intuitive situation arises since the mutual entropic information has *increased*, i.e. $h(I^{\star}_{mu}(k)) = -4.67$.

4.3.3 Identification Information

Here an identification estimator example is provided. Let the previous identification estimation be represented by the vector:

$$\mathbf{P}(\mathbf{X}|\mathbf{Z}^{k-1}) = \{0.8, 0.2\} \quad (4.16)$$

and the observation likelihood by:

$$\mathbf{P}(Z(k)|\mathbf{X}) = \{0.7, 0.3\}. \quad (4.17)$$

The combination of these values using the Bayesian identity estimator, see Section 3.3, provides the updated estimate as:

$$\mathbf{P}(\mathbf{X}|\mathbf{Z}^{k}) = \{0.9, 0.1\} \quad (4.18)$$

However, this is *not* equivalent to the addition of the *entropic information*, i.e. using Equation 4.6:

$$H(P(\mathbf{X}|\mathbf{Z}^{k}|k)) \neq H(P(\mathbf{X}|\mathbf{Z}^{k-1})) + H(P(Z(k)|\mathbf{X})) \quad (4.19)$$

or

$$(-0.32) \neq (-0.50) + (-0.61). \quad (4.20)$$

This situation arises since the mutual entropic information has not been taken into account, its value can be calculated from:

$$H(I_{mu}(k)) = H(P(\mathbf{X}|\mathbf{Z}^{k-1})) + H(P(Z(k)|\mathbf{X})) - H(P(\mathbf{X}|\mathbf{Z}^{k}|k)) \quad (4.21)$$

or

$$H(I_{mu}(k)) = (-0.50) + (-0.61) - (-0.32) = -0.79. \tag{4.22}$$

Further, if the entropic information content of the observation is *increased* by using $P^{\star}(Z(k)|\mathbf{X})$, i.e.:

$$P^{\star}(Z(k)|\mathbf{X}) = \{0.2, 0.8\} \tag{4.23}$$

that is $H(P^{\star}(Z(k)|\mathbf{X})) = -0.50$, the corresponding update entropic information *decreases* to $H(P^{\star}(\mathbf{X}|\mathbf{Z}^k)) = -0.69$. This counter intuitive situation arises since the mutual entropic information has *increased* to $H(I^{\star}_{mu}(k)) = -0.69$.

4.3.4 The Merits of Update Data for Decisions

The results of the above examples impley that increasing the observation entropic information does not necessarily increase the update entropic information. This counter intuitive situation arises when increasing the observation entropic information produces an even greater increase in the mutual entropic information. Therefore, making decisions on the basis of maximising the observation entropic information does not necessarily mean that the update entropic information will also be maximised. A similar argument can be put forward for the predicted entropic information.

The aim of this section was to answer the question '*what* stage of the data fusion process, i.e. predict, observe or update, should be used as a decision basis?' This was achieved by considering the effect of mutual information on combining the predicted and observed entropic information values. Simple examples showed that increasing the observation (or prediction) entropic information does not necessarily increase the update entropic information. Therefore, the decision goal of maximising the 'update' entropic information will not necessarily be achieved by maximising the predicted or observed entropic informations individually. To achieve this goal the entropic information of the combination of the predicted and observed data must be employed. In practice, these data may not be available and predictions of their values will be employed.

4.4 Information Gain

This section aims to answer the question 'what information gain basis are suitable for data fusion?' This is achieved by considering the relative and absolute information gains.

4.4.1 Relative Information Gain

Relative entropic information gain or the *Kullbak Leibler* distance between two different probability mass functions $p(x)$ and $q(x)$ is defined as (Cover and Thomas 1991):

$$D\left(\frac{p}{q}\right) = \int_{-\infty}^{\infty} p(x)\, \ln\left(\frac{p(x)}{q(x)}\right) dx. \tag{4.24}$$

For multi-dimensional Gaussian distributions this distance reduces to (Kastella 1996):

$$D\left(\frac{p}{q}\right) = -\ln\left[\frac{|\mathbf{P}|}{|\mathbf{Q}|}\right] \tag{4.25}$$

where $|\mathbf{P}|$ is the determinant of the covariance of the distribution $p(x)$ and $|\mathbf{Q}|$ is the determinant of the covariance of the distribution $q(x)$. It should be noticed that this is an asymmetric metric.

Employing the notation of Chapter 3 the relative gain for the update of a kinematic estimator is given by:

$$I_r^{Tr}(k) = -\ln\left[\frac{|\tilde{\mathbf{P}}(k|k)|}{|\tilde{\mathbf{P}}(k-1|k-1)|}\right] \tag{4.26}$$

or

$$I_r^{Tr}(k) = -\ln\left[\frac{|\tilde{\mathbf{Y}}(k|k)|^{-1}}{|\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}}\right] \tag{4.27}$$

where $I_r^{Tr}(k)$ is the relative (r) gain for a target's kinematic (Tr) estimate at a time k.

Previous work on applying information metrics for decision making in multi-target data fusion systems (Manyika and Durrant-Whyte 1994) have considered the relative gain on each target individually. The overall information gain is then calculated by summing the gains associated with each individual target. Hence, for multi-target applications Equation 4.27 becomes:

$$I_{rm}^{Tr}(k) = -\sum_{\forall t} \ln\left[\frac{|{}^t\tilde{\mathbf{Y}}(k|k)|^{-1}}{|{}^t\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}}\right]. \tag{4.28}$$

This can be re-written such that the information state values are multiplied:

$$I_{rm}^{Tr}(k) = -\ln\left[\frac{\prod_{\forall t} |{}^t\tilde{\mathbf{Y}}(k|k)|^{-1}}{\prod_{\forall t} |{}^t\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}}\right] \tag{4.29}$$

where $I_{rm}^{Tr}(k)$ is the relative information on all targets of index t.

For discrete distributions, such as those employed for target identification in Chapter 3, Equation 4.24 becomes:

$$I_r^{Id}(k) = \sum_{\forall X} P(X|\mathbf{Z}^k)\ln\left[\frac{P(X|\mathbf{Z}^k)}{P(X|\mathbf{Z}^{k-1})}\right] \tag{4.30}$$

where $I_r^{Id}(k)$ is the relative (r) gain for a target's identification (Id) estimate at a time k. Further, for multi-target applications Equation 4.30 becomes:

$$I_{rm}^{Id}(k) = \sum_{\forall t}\sum_{\forall X} {}^tP(X|\mathbf{Z}^k)\ln\left[\frac{{}^tP(X|\mathbf{Z}^k)}{{}^tP(X|\mathbf{Z}^{k-1})}\right] \tag{4.31}$$

where $I_{rm}^{Id}(k)$ is the relative identification information on all targets of index t.

4.4.2 Absolute Information

The absolute entropic information gain from one distribution, $p(x)$, to another, $q(x)$, is defined as:

$$D(p-q) = \int_{-\infty}^{\infty} p(x)\ \ln(p(x)) - q(x)\ \ln(q(x))dx. \tag{4.32}$$

For a multi-Gaussian distribution, as discussed in the kinematic estimators of Chapter 3, Equation 4.32 becomes:

$$I_a^{Tr}(k) = -\frac{1}{2}\ln[(2\pi e)^l|\tilde{\mathbf{P}}(k|k)|] + \frac{1}{2}\ln[(2\pi e)^l|\tilde{\mathbf{P}}(k-1|k-1)|] \tag{4.33}$$

or

$$I_a^{Tr}(k) = -\frac{1}{2}\ln\left[\frac{|\tilde{\mathbf{P}}(k|k)|}{|\tilde{\mathbf{P}}(k-1|k-1)|}\right] \tag{4.34}$$

or

$$I_a^{Tr}(k) = -\frac{1}{2}\ln\left[\frac{|\tilde{\mathbf{Y}}(k|k)|^{-1}}{|\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}}\right] \tag{4.35}$$

where $I_a^{Tr}(k)$ is the absolute (a) gain for a target's kinematic (Tr) estimate at a time k. The subtle difference in information distances becomes apparent for multi-target applications. Here the absolute entropic gain is to be calculated, this implies that the multi-target information values are summed and not multiplied as for the relative information.

Here Equation 4.35 becomes:

$$I_{am}^{Tr}(k) = -\frac{1}{2}\ln\left[\frac{\sum_{\forall t}|{}^t\tilde{\mathbf{Y}}(k|k)|^{-1}}{\sum_{\forall t}|{}^t\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}}\right] \tag{4.36}$$

where $I_{am}^{Tr}(k)$ is the absolute entropic information on all targets of index t.

For discrete distributions, such as those employed for target identification in Chapter 3, Equation 4.32 becomes:

$$I_a^{Id}(k) = \sum_{\forall X} P(X|\mathbf{Z}^k)\ln(P(X|\mathbf{Z}^k)) - \sum_{\forall X} P(X|\mathbf{Z}^{k-1})\ln(P(X|\mathbf{Z}^{k-1})) \tag{4.37}$$

where $I_a^{Id}(k)$ is the absolute (a) gain for a target's identification (Id) estimate at a time k. Further, for multi-target applications Equation 4.37 becomes:

$$I_{am}^{Id}(k) = \sum_{\forall t}\sum_{\forall X} {}^tP(X|\mathbf{Z}^k)\ln({}^tP(X|\mathbf{Z}^k)) - \sum_{\forall t}\sum_{\forall X} {}^tP(X|\mathbf{Z}^{k-1})\ln({}^tP(X|\mathbf{Z}^{k-1})) \tag{4.38}$$

where $I_{am}^{Id}(k)$ is the absolute entropic gain on all targets of index t.

4.4.3 Examples of Relative and Absolute Information

This section provides two simple data fusion examples. The aim here is to show that decisions based on relative and absolute entropic information gains can result in different actions.

Kinematic Example

First consider a kinematic example: a decision has to made on updating one of two estimators due to an action (e.g. sensor management or communications management). The expected certainty associated with the estimators at time index k and $k-1$ are provided below:

$$ {}^1\tilde{\mathbf{Y}}(k-1|k-1) = \begin{bmatrix} 0.1 & 0.0 \\ 0.0 & 0.1 \end{bmatrix}, \quad {}^1\tilde{\mathbf{Y}}(k|k) = \begin{bmatrix} 0.2 & 0.0 \\ 0.0 & 0.2 \end{bmatrix} \tag{4.39}$$

and

$$ {}^2\tilde{\mathbf{Y}}(k-1|k-1) = \begin{bmatrix} 0.01 & 0.0 \\ 0.0 & 0.01 \end{bmatrix}, \quad {}^2\tilde{\mathbf{Y}}(k|k) = \begin{bmatrix} 0.011 & 0.0 \\ 0.0 & 0.011 \end{bmatrix}. \tag{4.40}$$

Therefore, considering the relative gain, an action on target 1 would result in the following decision value:

$$I_{rm}^{Tr}(k) = -\ln\left[\frac{\frac{1}{0.2^2}\cdot\frac{1}{0.01^2}}{\frac{1}{0.1^2}\cdot\frac{1}{0.01^2}}\right] = 1.386, \tag{4.41}$$

and an action on target 2 would result in the following decision value:

$$I_{rm}^{Tr}(k) = -\ln\left[\frac{\frac{1}{0.1^2}\cdot\frac{1}{0.011^2}}{\frac{1}{0.1^2}\cdot\frac{1}{0.01^2}}\right] = 0.190. \tag{4.42}$$

Hence, maximising the relative gain would result in an action on the kinematic estimation of target 1.

Next, we consider the absolute gain. Here an action on target 1 would result in the following decision value:

$$I_{am}^{Tr}(k) = -\frac{1}{2}\ln\left[\frac{\frac{1}{0.2^2}+\frac{1}{0.01^2}}{\frac{1}{0.1^2}+\frac{1}{0.01^2}}\right] = 0.004, \tag{4.43}$$

and an action on target 2 would result in the following decision value:

$$I_{am}^{Tr}(k) = -\frac{1}{2}\ln\left[\frac{\frac{1}{0.1^2}+\frac{1}{0.011^2}}{\frac{1}{0.1^2}+\frac{1}{0.01^2}}\right] = 0.09. \tag{4.44}$$

Hence, maximising the absolute gain would result in an action on the kinematic estimator of target 2. Therefore the relative and absolute gains have resulted in different data fusion decisions being made.

Similar simple examples that demonstrate coincident decisions being made can easily be thought up, e.g. :

$$^{1}\tilde{\mathbf{Y}}(k-1|k-1) = \begin{bmatrix} 0.1 & 0.0 \\ 0.0 & 0.1 \end{bmatrix}, \quad ^{1}\tilde{\mathbf{Y}}(k|k) = \begin{bmatrix} 0.2 & 0.0 \\ 0.0 & 0.2 \end{bmatrix} \tag{4.45}$$

and

$$^{2}\tilde{\mathbf{Y}}(k-1|k-1) = \begin{bmatrix} 0.01 & 0.0 \\ 0.0 & 0.01 \end{bmatrix}, \quad ^{2}\tilde{\mathbf{Y}}(k|k) = \begin{bmatrix} 0.025 & 0.0 \\ 0.0 & 0.025 \end{bmatrix}. \tag{4.46}$$

Here the action on target 2 would be chosen for both relative and absolute gains.

Identification Example

Lets now consider an identification example: a decision has to be made on updating one of two identification estimates due to an action (e.g. sensor management or communications management). The expected identity vectors associated with the estimates at time index k and $k-1$ are provided below:

$$^{1}P(\mathbf{X}|\mathbf{Z}^k) = \{0.7, 0.3\}, \quad ^{1}P(\mathbf{X}|\mathbf{Z}^{k-1}) = \{0.5, 0.5\} \tag{4.47}$$

and

$$^{2}P(\mathbf{X}|\mathbf{Z}^{k}) = \{0.85, 0.15\}, \quad ^{2}P(\mathbf{X}|\mathbf{Z}^{k-1}) = \{0.7, 0.3\}. \tag{4.48}$$

Therefore, considering the relative gain, an action on target 1 would result in the following decision value:

$$\begin{aligned} I^{Id}_{rm}(k) &= (0.7\ \ln\left(\tfrac{0.7}{0.5}\right)) - (0.3\ \ln\left(\tfrac{0.3}{0.5}\right)) \\ &= 0.082 \end{aligned} \tag{4.49}$$

and an action on target 2 would result in the following decision value:

$$\begin{aligned} I^{Id}_{rm}(k) &= (0.85\ \ln\left(\tfrac{0.85}{0.7}\right) - (0.15\ \ln\left(\tfrac{0.15}{0.3}\right)) \\ &= 0.061. \end{aligned} \tag{4.50}$$

Hence, maximising the relative gain would result in an action on the identification estimator of target 1.

Next, we consider the absolute entropic gain, an action on target 1 would result in the following decision value:

$$\begin{aligned} I^{Id}_{am}(k) &= 0.7\ \ln\ (0.7) + 0.3\ \ln\ (0.3) \\ &\quad +\ 0.5\ \ln\ (0.5) + 0.5\ \ln\ (0.5) \\ &= 0.082 \end{aligned} \tag{4.51}$$

and an action on target 2 would result in the following decision value:

$$\begin{aligned} I^{Id}_{am}(k) &= 0.85\ \ln\ (0.85) + 0.15\ \ln\ (0.15) \\ &\quad +\ 0.7\ \ln\ (0.7) + 0.3\ \ln\ (0.3) \\ &= 0.188. \end{aligned} \tag{4.52}$$

Hence, maximising the absolute entropic gain would result in an action on the identification estimator of target 2. Again, the relative and absolute entropic gains result in different actions.

Simple examples that demonstrate coincident decisions being made can easily be thought up, e.g. :

$$^{1}P(\mathbf{X}|\mathbf{Z}^{k}) = \{0.7, 0.3\}, \quad ^{1}P(\mathbf{X}|\mathbf{Z}^{k-1}) = \{0.5, 0.5\} \tag{4.53}$$

and

$$^{2}P(\mathbf{X}|\mathbf{Z}^{k}) = \{0.95, 0.05\}, \quad ^{2}P(\mathbf{X}|\mathbf{Z}^{k-1}) = \{0.7, 0.3\}. \tag{4.54}$$

Here the action on target 2 would be chosen for both gains.

Summary of Information Distances

Relative Information

$$I_{rm}^{Tr}(k) = -\ln\tfrac{1}{2}[\Pi_{\forall t}|{}^t\tilde{\mathbf{Y}}(k|k)|^{-1}] + \ln\tfrac{1}{2}[\Pi_{\forall t}|{}^t\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}]$$

$$I_{rm}^{Id}(k) = \Sigma_{\forall t}\Sigma_{\forall X}\,{}^tP(X|\mathbf{Z}^k)\ln({}^tP(X|\mathbf{Z}^k)) - \Sigma_{\forall t}\Sigma_{\forall X}\,{}^tP(X|\mathbf{Z}^k)\ln({}^tP(X|\mathbf{Z}^{k-1}))$$

Absolute Information

$$I_{am}^{Tr}(k) = -\tfrac{1}{2}\ln[\Sigma_{\forall t}|{}^t\tilde{\mathbf{Y}}(k|k)|^{-1}] + \tfrac{1}{2}\ln[\Sigma_{\forall t}|{}^t\tilde{\mathbf{Y}}(k-1|k-1)|^{-1}]$$

$$I_{am}^{Id}(k) = \Sigma_{\forall t}\Sigma_{\forall X}\,{}^tP(X|\mathbf{Z}^k)\ln({}^tP(X|\mathbf{Z}^k)) - \Sigma_{\forall t}\Sigma_{\forall X}\,{}^tP(X|\mathbf{Z}^{k-1})\ln({}^tP(X|\mathbf{Z}^{k-1}))$$

Table 4.1: Relative and absolute entropic information gains

4.4.4 The Merits of Relative and Absolute Information

Effectively, for multi-sensor and multi-target sensing systems *relative* information is concerned with decisions that maximise the proportional change in uncertainty. In contrast, *absolute* information is concerned with maximising the difference in uncertainty. These information values have similarities coupled with subtle differences. The equations are summarised in Table 4.1:

The choice of which information value to employ will be dependent on the specification and requirements of the data fusion system.

The aim of this section was to answer the question '*what* information gain basis are suitable for data fusion?' This was achieved by stating two different metrics for entropic information gain. The first is based on relative gain, the second on absolute gain. Both have application for decision making in multi-target data fusion systems. Further, the decisions made are not necessarily the same. Simple data fusion examples for kinematic and identity estimators are provided where relative and absolute entropic gains provide decisions that are different and the same. For the work presented in this thesis absolute entropic information gain will be employed. This choice is based on the fact that this metric has not, to date, been applied to decentralised kinematic estimation management.

4.5 Decision Theory Techniques

This section aims to answer the question 'what decision theory techniques are applicable to communications management in decentralised systems?' This is achieved by providing brief overviews of applicable techniques and the contribution they make to communications management in decentralised systems as described in this dissertation.

4.5.1 Utility Theory

Here the powerful tool of *utility theory* is introduced. Within data fusion systems utility theory allows the *objective* information generated by the sensors and process models to be combined with *subjective* information provided by the system user.

A general description of utility theory can be found in (Berger 1980). In addition, its application to decentralised systems is discussed in (Manyika and Durrant-Whyte 1994). Both these references provide a description of the utility theory axioms. As such, they are not documented here.

For the work presented in this dissertation utility theory is employed as a sound theoretical basis for combining the absolute kinematic entropic information gain with the absolute identification entropic information gain to provide a system level target based decision value.

This is achieved by defining utilities based on:

$$U(\mathrm{x}) = I_{am}^{Tr}(k), \tag{4.55}$$

and:

$$U(\mathbf{X}) = I_{am}^{Id}(k). \tag{4.56}$$

Further, these utilities can be combined to provide a system level target based decision value, defined as:

$$U(\theta) = \alpha U(\mathrm{x}) + (1-\alpha)U(\mathbf{X}) \tag{4.57}$$

where $0 \leq \alpha \leq 1$ and θ is a state that linearly combines $\mathbf{x}$ and $\mathbf{X}$. An appropriate value for α would be chosen dependent on the relative weighting the system specification (as provided by the system user) places on kinematic and identification information.

4.5.2 Graphical Techniques for Decision Making

A number of graphical methods exist for usefully displaying the decisional problem (Pearl 1995) (Russell and Norvig 1995) (Chernoff and Moses 1959). The decision problem of communications management in decentralised systems can be represented by such techniques. In this section the communications management problem is formulated as a decision tree.

Decision trees comprise parent and child nodes which represent states. These are linked by arrowed lines which indicate the transition from a parent to a child node. These indicate the choices available to a decision maker. The tree shows the decision sequence required to achieve a given state after a given number of transitions. Such a tree is represented in Figure 4.3. Here state $I0$ can be achieved from state $I0$ by carrying out the actions associated with decision sequence $d1$, $d4$ and $d10$.

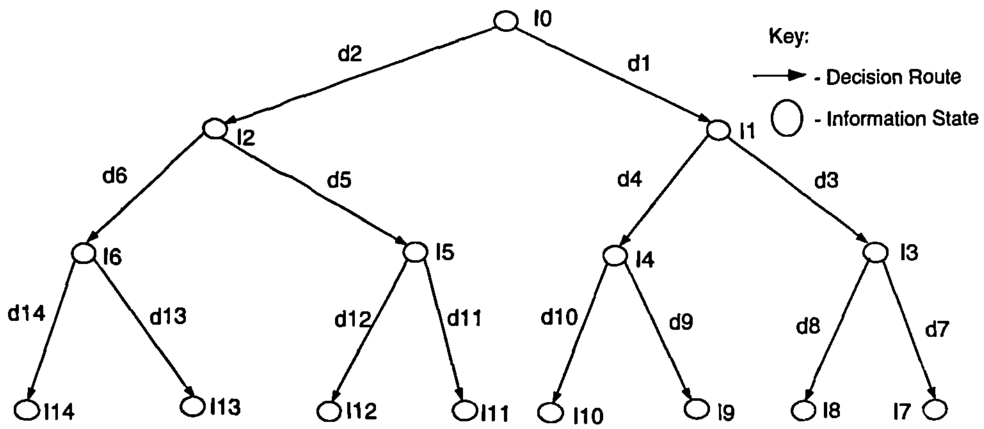


Figure 4.3: Binary symmetric decision tree.

A decision tree for communications management in decentralised systems is now constructed. Consider a simple example comprising two sensing nodes and two targets. This configuration is represented in Figure 4.4(a). Here each sensing node views each target. Further, it is assumed that the sensors observations and inter-nodal communications are synchronised. In addition, the inter-nodal communications bandwidth allows data on only a single target to be communicated in the time period between two consecutive sensor readings.

The decision tree for this simple hypothetical example is provided in Figure 4.4(b). At a time referred to by index k the total entropic information of all the sensing nodes, comprising kinematic and identification information combined by utility theory, is represented by $I0$. One of four possible decisions can then be made:

- d1: N1 to communicate to N2 on T1.
- d2: N1 to communicate to N2 on T2.

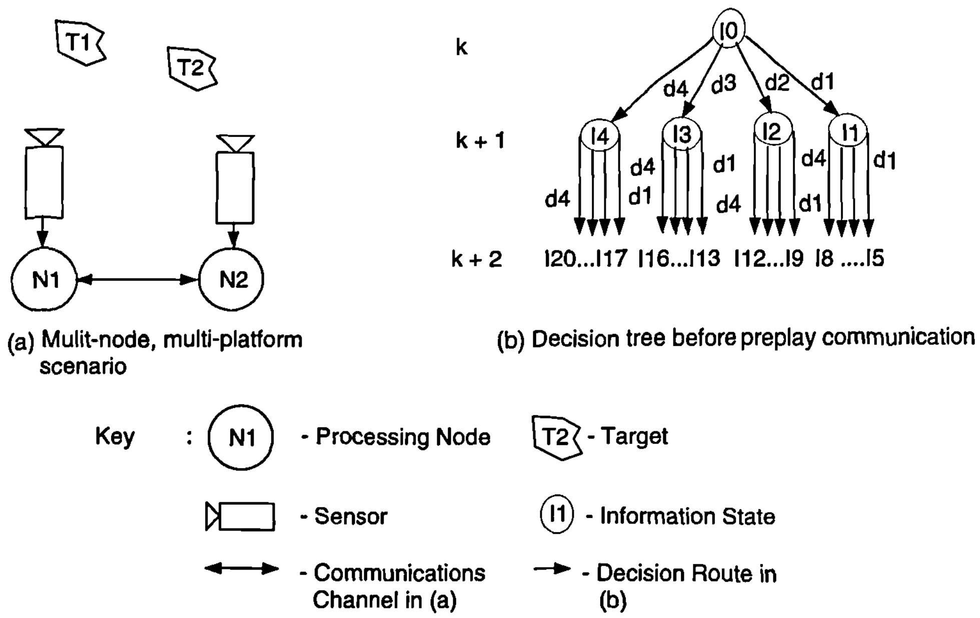


Figure 4.4: A simple communications management example.

- d3: N2 to communicate to N1 on T1.
- d4: N2 to communicate to N1 on T2.

Each decision results in the generation of corresponding child nodes, i.e. $I1 \dots I4$. These occur at time index $k+1$ and are spawned from the parent node $I0$. At the next iteration, time index $k+2$, $I1 \dots I4$ themselves become parent nodes which spawn child nodes dependent on the communication decision $d1 \dots d4$. These result in the generation of child nodes $I5 \dots I20$.

In this simple hypothetical example let us assume that the total entropic information at any tree node can be predicted precisely by each sensing node. It would then be possible for the sensing nodes to coherently choose an appropriate sequence of decisions, corresponding to communications, to achieve some goal, i.e. maximising the total entropic information at a time index $k+2$ by using the absolute information gain.

However, generally for sensing systems an inaccuracy is associated with predicting the sensing nodes state. This can be due to a number of factors, e.g. inaccuracy associated with observations and state predictions that will be made for time index $k+1 \dots k+2$ given the estimates available at time index k. Therefore, the information values $I1 \dots I20$ will be inaccurate and will differ at each of the sensing node. This gives rise to a number of problems for communications management in decentralised systems. These include:

1. The accuracy of the predictions of total entropic information reduces as the prediction sequence becomes longer. For the example above, generally, the predictions

of $I1 \ldots I4$ will be more accurate than those made for $I5 \ldots I20$. This makes long decision sequences undesirable.

2. Coherent inter-nodal communications is dependent on each sensing node having accurate and identical predictions of the total entropic information. If this is not the case then communication confusion can occur. For the example above, both sensing nodes $N1$ and $N2$ may wish to transmit simultaneously or receive simultaneously.

These problems motivate that the decentralised communications management algorithm described in this dissertation employs the minimum prediction step, i.e. over a single transmission, and that the communication order be pre-defined.

These constraints also provide the additional benefits of (i) reducing the computational cost associated with large numbers of information states, and (ii) reducing overhead communications required to overcome communication confusion.

The aim of this section was to answer the question '*what* decision theory techniques are applicable to communications management in decentralised system?' Utility theory was briefly reviewed and its application for combining target kinematic and identification entropic information gains discussed. This allows the generation of a system level target based entropic information metric. Graphical decision techniques were applied to the problem of communications management in decentralised systems by way of a simple example. This highlighted a couple of problems that arise from having an inaccurate prediction of the overall entropic information of the system. Further, these problems motivate a communications management algorithm that employs a single transmission prediction step, and a pre-defined communication order.

4.6 Summary and Concluding Remarks

This chapter began by stating a number of questions derived from 'what are the information metrics and decision techniques used in the thesis?' These have been answered in the sections of the chapter. Here these are used to answer the following question 'why are they being employed?'

- *'Why entropic information?'*
  Entropic information provides a number of advantages that motivate its use for communications management in decentralised systems. These include: (i) its application to kinematic and identification estimators, (ii) it provides a scalar quantity that makes it suitable for decision making, and (iii) it has already been successfully applied in decentralised sensor management.

- *'Why update information?'*
  The effect of mutual information on kinematic and identification estimators can lead to an incorrect management decision being made in decentralised systems. This is true if the management decisions are made based on maximising the observed[1] entropic information alone with the intuitive expectation that the update information will also be maximised. This motivates the use of the update information, or a prediction of it, as an information decision basis for communications management.

- *'Why absolute information gain?'*
  Absolute information gain provides a measure of the overall change in entropic information. This metric is employed as it has not previously been applied to decentralised kinematic estimation management. As such, it provides a further **original** aspect to the thesis.

- *'Why utility theory?'*
  Utility theory provides a sound theoretical basis for combining kinematic and identification data. Within the context of communications management it is employed to combine absolute entropic information gains for the target kinematics and identification attributes to provide a system level target based decision value.

- *'Decisional trees?'*
  The use of graphical decisional trees can be used to represent the decision problem encountered in the communications management of decentralised sensing systems. Further, the inaccuracies associated with sensing nodes predicting the system information state can lead to two problems: (i) sub-optimal decision routes through the decision tree, and (ii) confused communications that result in either no sensing node utilising the communications resource or a number of nodes in conflict for its use. These problems motivate two constraints on the the communications management: (i) that the prediction step be limited to a single transmission, and (ii) that the communications resource has a pre-defined nodal transmission sequence.

[1] Or predicted/previous estimates.

The answers to these questions provide the management capabilities for the thesis. These are now stated:

> The communications management algorithms investigated in this thesis are based on entropic information applied to the estimators update (or prediction of it). Further, decision values are calculated based on the absolute gains for kinematic and identification information individually. In addition, utility theory is used to combine these to provide a system level target based information gain.
> An investigation of the communications management decision tree indicated two problems that could be overcome by applying the following constraints: (i) the prediction stage of the communications management algorithm will be over a single transmission, and (ii) there will be a pre-defined communication sequence for the sensing nodes.

Chapter 5

Communications Management in Decentralised Systems

5.1 Introduction

The aim of this chapter is to answer the question '*How* will communications management be implemented, evaluated and applied in the context of this thesis?' These answers provide the test-bed capability and hypotheses of the thesis.

The mapping between these questions and sections of the chapter are provided in Figure 5.1. Since this chapter is focussed (partly) on the implementation of communications management, the kinematic algorithm is referred to as a *tracking* algorithm here and for the remainder of the dissertation. This is motivated since simple data association is applied for observation to track assignment. Further, the implementation is concerned with the simulation of fighter aircraft. Therefore, the term 'node' is replaced with the term 'platform'. No loss of generality follows from this use of specific terminology.

The remainder of this chapter is organised as follows: Section 5.2 provides a brief review of decentralised sensing systems resources and their management. The implementation details of a channel filter applied to dealing with bandwidth constraints is provided in Section 5.3. This leads to a discussion on the implementation of communications management in Section 5.4. Section 5.5 provides the details of the performance metrics used in the thesis and a method for determining potential trade-off issues. Sections 5.6 and 5.7 derive hypotheses relating to *evaluating* and *applying* communications management respectively. A summary and concluding remarks on the implementation, evaluation and application of communications management is provided in Section 5.8.

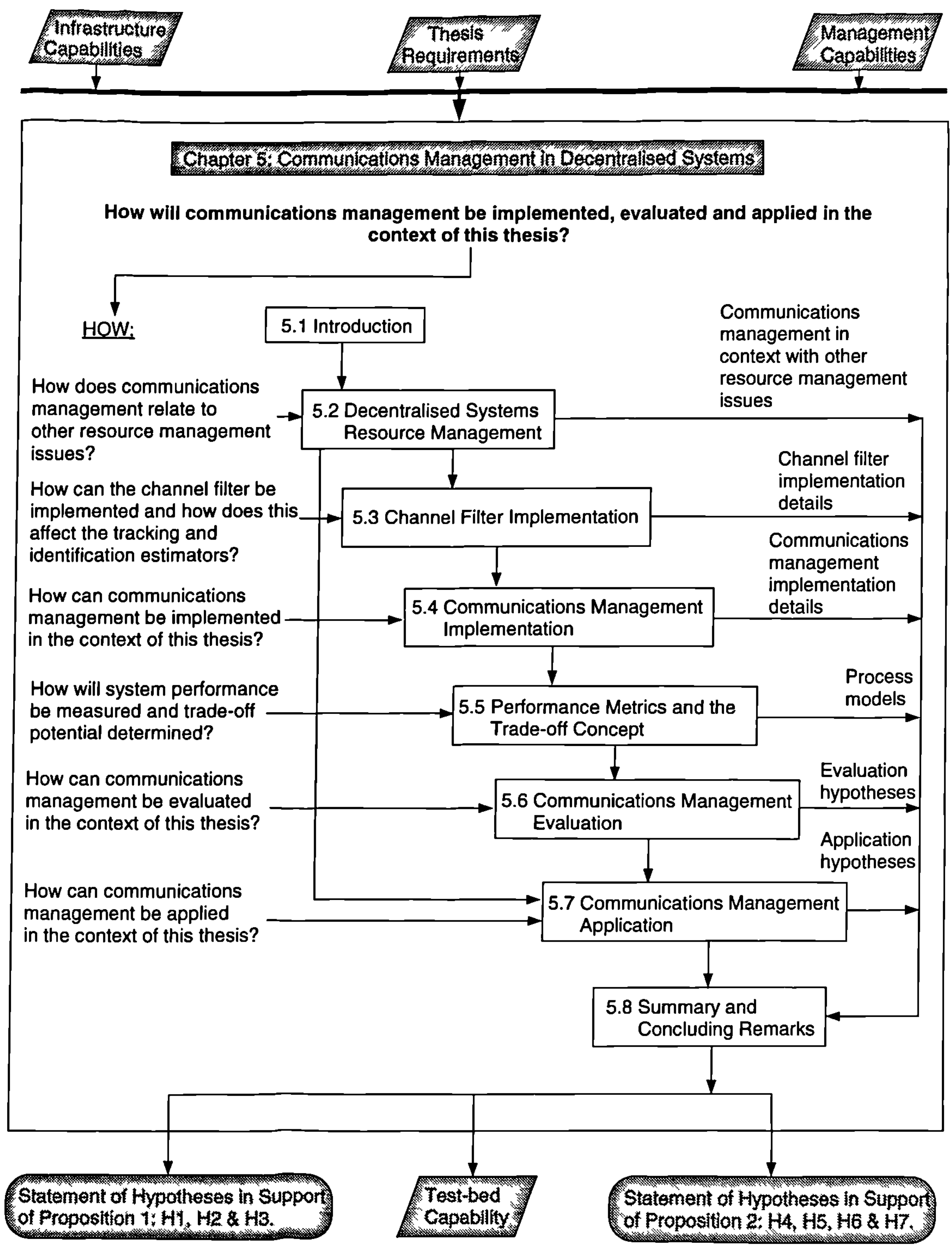


Figure 5.1: Reader's map for Chapter 5.

5.2 Decentralised Systems Resource Management

This section aims to answer the question 'how does communications management relate to other resource management issues?' This is achieved by reviewing these resources and their management.

5.2.1 Sensing System Resources

Here details of some of the resources available in a multi-platform decentralised sensing system are provided. Figure 5.2 represents communications, sensing, processing resources and multi-platform operation. These are discussed below:

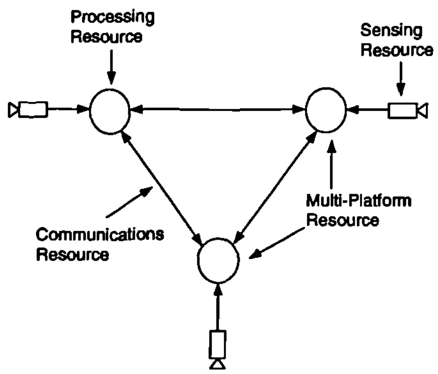


Figure 5.2: Decentralised sensing system resources.

Communications

The communications resource in a decentralised system provides a mechanism for the platforms to exchange data. In the context of the sensing systems in this thesis, these data will be based on target track or identification estimates.

If the communications resource is unconstrained in bandwidth and latency, then the system performance can be maximised, given other system constraints. If the communications resource is so constrained that no data may flow between the processing resources then each platform acts independently. This provides minimum system performance. For communications constraints that lie between these two extremes, i.e. full bandwidth and zero bandwidth, the system performance changes between the maximum and minimum levels.

A host of internal and external parameters characterise the performance of a communications system. These include bandwidth, communications protocol, latency, probability of a communications being successful and environmental conditions.

Processors

The processing platforms of a decentralised system have data input from the sensor, other platforms, and prior knowledge concerning the target. This is assimilated in order to provide target data in the form of track and identification estimates.

The primary performance characteristic for a decentralised processing platform is its processing speed, i.e. how many processor instructions it carries out per second. A high performance processor may be able to update its estimates each time a new observation or communication is obtained. However, a low performance processor may have to ignore some sensor and communications data. This results in tracking estimators with higher uncertainties and identification estimators that have slower convergence times. Further, high performance processors may be able to employ more complex (high performance) estimation algorithms. In addition, they may be able to carry out other tasks that enhance system performance, e.g. resource management (see Section 5.2.2).

Sensors

The sensing resource in a decentralised system provides the processing platforms with data about the 'real' world. For many sensors these data are in the form of an electrical signal. Often the sensor is accompanied by a pre-processing unit which converts the electrical signal into a more meaningful or useful measure. For simple sensors this could comprise a basic analogue-to-digital conversion. For more sophisticated sensors, such as radars, a tracking system may be employed that provides an estimate of a target's location/velocity along with an associated covariance measure.

A host of parameters characterise the performance of a sensor. These include: maximum and minimum range, probability of detection, resolution, update rate and output - range profile. A sensor with a poor performance generally has low performance characteristics. Conversely, high performance sensors score high characteristic values.

Number of Platforms

In decentralised sensing systems the performance of the system can often be increased by introducing additional processing platforms. For target tracking systems this increase in performance manifests itself as reduced uncertainty about the estimate, i.e. reduction in $|\mathbf{P}|$. For target identification the increase in performance results in a reduced target identification time, i.e. time taken for the largest target class probability value to exceed some threshold.

The number of platforms that make-up a system will be limited due to system cost. The minimum system performance generally occurs when the system comprises only one platform.

5.2.2 Resource Management

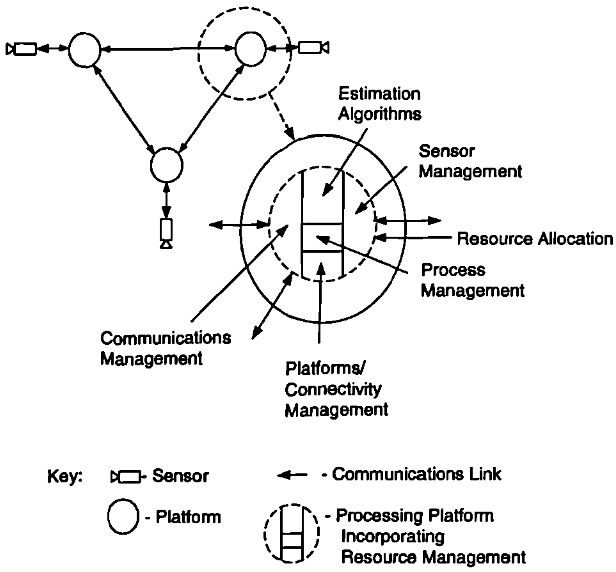


Figure 5.3: Decentralised sensing system resource management.

The effective performance of communications, sensor, processor and number of platforms can be enhanced by the application of resource management. These are represented in Figure 5.3. Here the processing allocation on one of the platforms has been expanded. This overall processing resource comprises management functions concerned with sensor, communications, platforms/connectivity and processing as well as the estimation algorithms. The management processes are concerned with the intelligent control of a resources such that its utilisation maximises system performance. However, this effective increase in performance is at the expense of increased computational cost which is passed on to the processing resource.

Limited research has been carried out in the area of decentralised communications resource management. (Grime 1993) investigates the reduction in bandwidth requirement that is brought about by non-fully connected systems. An information theoretic approach to decentralised sensor management is described in (Manyika and Durrant-Whyte 1994). Within the decentralised sensing system community, not much work has been done on process management, although algorithms with a reduced computational requirement have been sought, e.g. the information filter (Mutambara and Durrant-Whyte 1994). Resource management of the number of platforms and their connectivity have been investigated by (Utete 1994) and (Ho 1994).

An important question that remains unanswered in the technological area of decentralised systems is how these different management strategies interact. A sensible approach to this problem is to consider each individually first. Since communications management has not been considered, it provides the first research area for this thesis, an *evaluation* of communications management. This is represented in **Proposition 1** of the thesis, see page 1.

When the management of these resources have been considered individually, the next logical step to take is to consider them employed collectively. This is outside the scope of this thesis. However, the interaction of communications management with fixed processors, sensors and number of platforms is considered. This forms, coupled with the avionic requirements outlined in Section 2.6, the second research area of the thesis, the *application* of communications management to the investigation of system design trade-offs in avionic systems. This is represented in **Proposition 2** of the thesis, see page 1.

> This section has answered the question 'how does communications management relate to other resource management issues?' This has been achieved by considering the resources in a decentralised system, i.e. communications, processor, sensor and number of platforms. Further, brief details of work carried-out on managing these resources has been provided. This leads to the development of the communications management research areas in the context of this thesis: (i) an *evaluation* of communications management, and (ii) its *application* to the problem of avionic system design trade-offs. See **Propositions 1 and 2** on page 1, respectively.

5.3 Channel Filter Implementation

This section of the thesis aims to answer the question 'how can the channel filter be implemented and how does it affect the tracking and identification performance?' The use of the channel filter in a single target bandwidth constrained decentralised systems has already been briefly considered, from an information graph viewpoint, in Chapter 3.

5.3.1 Channel Filters for Bandwidth Constrained Links

In this section implementation details of applying channel filters to bandwidth constrained links are provided.

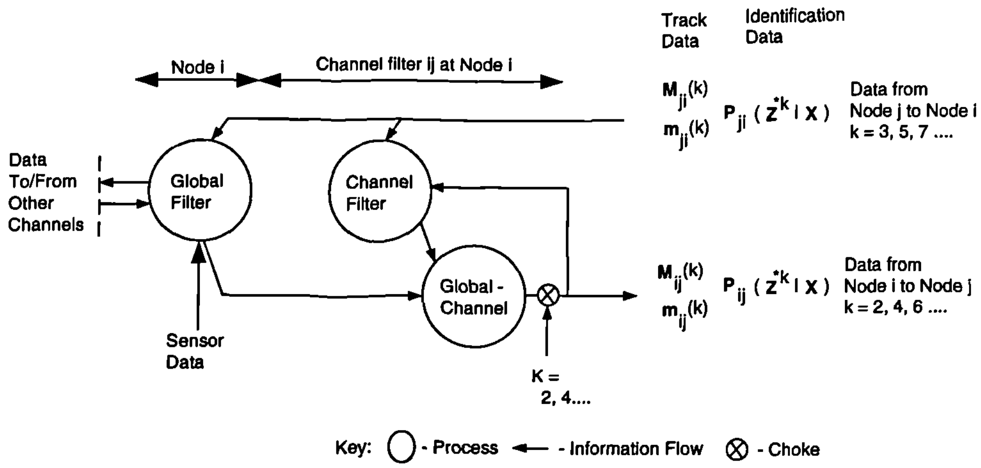


Figure 5.4: Functionality of the channel filter for bandwidth constrained links.

The operation of the channel filter for dealing with a bandwidth constrained link is represented in Figure 5.4. Here a 'choke' has been placed on the output limb of the channel filter. This choke is matched to the bandwidth of the communications link. For the example shown in Figure 5.4 the bandwidth of the communication link constrains transmission of the output data to 1 in 2, i.e. $k = 2, 4, 6 \ldots$. This data is calculated from the global and channel filter data as:

Global Track Filter	**Global Identification Filter**
$\tilde{\mathbf{Y}}_i(k\|k)$	$P_i(\mathbf{X}\|\mathbf{Z}^k)$
$\tilde{\mathbf{y}}_i(k\|k)$	
Channel Track Filter	**Channel Identification Filter**
$\tilde{\mathbf{Y}}_{ij}(k\|k)$	$P_{ij}(\mathbf{X}\|\mathbf{Z}^k)$
$\tilde{\mathbf{y}}_{ij}(k\|k)$	
Track Transmission Data	**Identification Transmission Data**
$\mathbf{M}_{ij}(k) = \tilde{\mathbf{Y}}_i(k\|k) - \tilde{\mathbf{Y}}_{ij}(k\|k)$	$P_{ij}(\mathbf{Z}^{*k}\|\mathbf{X}) = \frac{P_i(\mathbf{X}\|\mathbf{Z}^k)}{P_{ij}(\mathbf{X}\|\mathbf{Z}^k)} \times C_k$
$\mathbf{m}_{ij}(k) = \tilde{\mathbf{y}}_i(k\|k) - \tilde{\mathbf{y}}_{ij}(k\|k)$	

Table 5.1: Transmission data calculations.

For the tracking estimator the update interval of the global and channel filters has to be synchronised. The motivation for this is discussed in the next section.

5.3.2 Updating Global and Channel Filters

When the channel filter is applied to a constrained bandwidth communication link, the temptation exists to update the tracking channel estimator less often than its associated global estimator. This method provides a computational advantage when compared to updating the channel filter at each time step.

However, caution should be exercised in applying this technique since the translation of the continuous process noise to a discrete value is only an approximation. Hence, predicting a covariance by two time steps of value ΔT is not equivalent to predicting this value by a single time step of $2 \times \Delta T$ [1]. This is now demonstrated by a simple example: Consider a global tracking estimator which has an identical estimate (state and covariance) as a channel filter. This situation could arise if the first communication out of the channel had just occurred and no inward communications had been received. Assume that the next communication out of the channel is due to take place after 2 seconds. Further, the update rate of the global filter is 1 second. A timing diagram of this arrangement is shown in Figure 5.5(a).

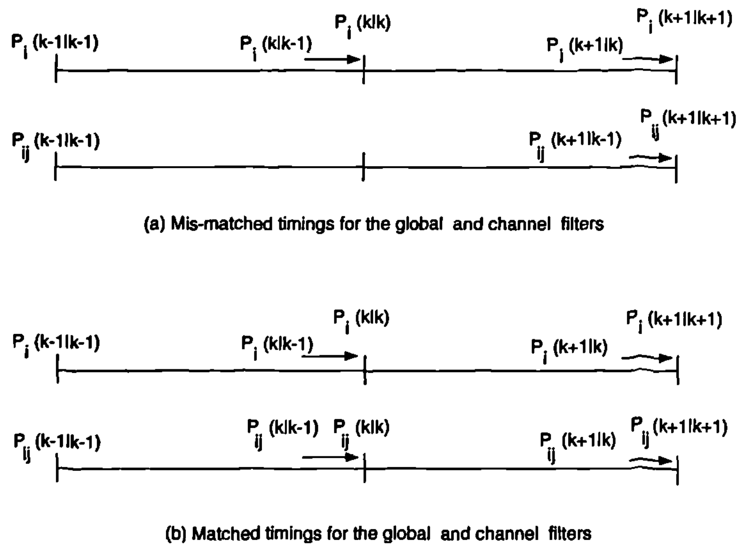


Figure 5.5: Global and channel filter timing diagrams.

During the two updates of the global filter no information is received from the sensor or from any of the channel filters. Hence it would be expected that the next communication down the channel would contain no information, i.e. the channel information and global information should be equal, or for a tracking example the covariances should be equal.

[1] If the process noise variance is constant.

An example calculation is now given: The global filter is updated every second using the generic algorithm:

$$\hat{\mathbf{P}}(k|k-1) = \mathbf{F}(k)\tilde{\mathbf{P}}(k-1|k-1)\mathbf{F}^T(k) + \mathbf{Q}(k) \tag{5.1}$$

or, in this case,

$$\hat{\mathbf{P}}_i(k|k-1) = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} + \begin{bmatrix} \frac{1}{4} & \frac{1}{3} \\ \frac{1}{3} & 1 \end{bmatrix} \tag{5.2}$$

which gives:

$$\hat{\mathbf{P}}_i(k|k-1) = \begin{bmatrix} \frac{9}{4} & \frac{4}{3} \\ \frac{4}{3} & 2 \end{bmatrix}. \tag{5.3}$$

Since no other information is received by the global filter the update becomes:

$$\tilde{\mathbf{P}}_i(k|k) = \hat{\mathbf{P}}_i(k|k-1) \tag{5.4}$$

or

$$\tilde{\mathbf{P}}_i(k|k) = \begin{bmatrix} \frac{9}{4} & \frac{4}{3} \\ \frac{4}{3} & 2 \end{bmatrix}. \tag{5.5}$$

This update is again predicted to give:

$$\hat{\mathbf{P}}_i(k+1|k) = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{9}{4} & \frac{4}{3} \\ \frac{4}{3} & 2 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} + \begin{bmatrix} \frac{1}{4} & \frac{1}{3} \\ \frac{1}{3} & 1 \end{bmatrix} \tag{5.6}$$

which becomes:

$$\hat{\mathbf{P}}_i(k+1|k) = \begin{bmatrix} \frac{86}{12} & \frac{11}{3} \\ \frac{11}{3} & 3 \end{bmatrix}. \tag{5.7}$$

Again, since no other information is obtained:

$$\tilde{\mathbf{P}}_i(k+1|k+1) = \hat{\mathbf{P}}_i(k+1|k) \tag{5.8}$$

or

$$\tilde{\mathbf{P}}_i(k+1|k+1) = \begin{bmatrix} \frac{86}{12} & \frac{11}{3} \\ \frac{11}{3} & 3 \end{bmatrix}. \tag{5.9}$$

For the channel filter a single prediction is calculated:

$$\hat{\mathbf{P}}_{ij}(k+1|k-1) = \begin{bmatrix} 1 & 2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 2 & 1 \end{bmatrix} + \begin{bmatrix} 4 & \frac{8}{3} \\ \frac{8}{3} & 4 \end{bmatrix} \tag{5.10}$$

which gives:

$$\hat{\mathbf{P}}_{ij}(k+1|k-1) = \begin{bmatrix} 9 & \frac{14}{3} \\ \frac{14}{3} & 5 \end{bmatrix}. \tag{5.11}$$

Further, no other information is obtained by the channel filter. Hence:

$$\tilde{\mathbf{P}}_{ij}(k+1|k+1) = \hat{\mathbf{P}}_{ij}(k+1|k-1) \tag{5.12}$$

or

$$\hat{\mathbf{P}}_{ij}(k+1|k+1) = \begin{bmatrix} 9 & \frac{14}{3} \\ \frac{14}{3} & 5 \end{bmatrix}. \tag{5.13}$$

Since Equations 5.9 and 5.13 are not identical the channel filter has failed in its function. This situation results in the communication of information although no new data had been input to the system. This undesirable effect can be overcome if the update rate for the global and channel filters are identical, see Figure 5.5(b).

5.3.3 The Effects of Bandwidth Constraint

In this section of the dissertation a discussion is provided on the effect communications bandwidth constraint has on decentralised tracking and identification estimators.

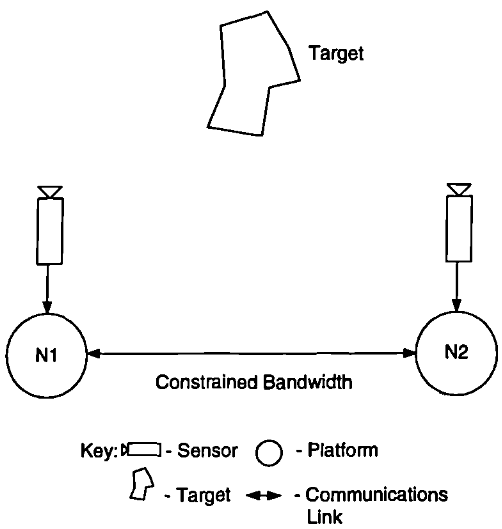


Figure 5.6: A bandwidth constrained example.

First an example is described, see Figure 5.6. Here a single target is observed by two platforms. Further, the inter-platform communications bandwidth has been reduced so that only one communication is made on the target for every four local sensor updates, i.e. 25% of full bandwidth.

Figures 5.7 (a) and (b) represent the results obtained from the simple example. These are enhanced by the full bandwidth results, i.e. those obtained when the bandwidth is not constrained, and the zero bandwidth results, i.e. those obtained when no data is communicated between the platforms.

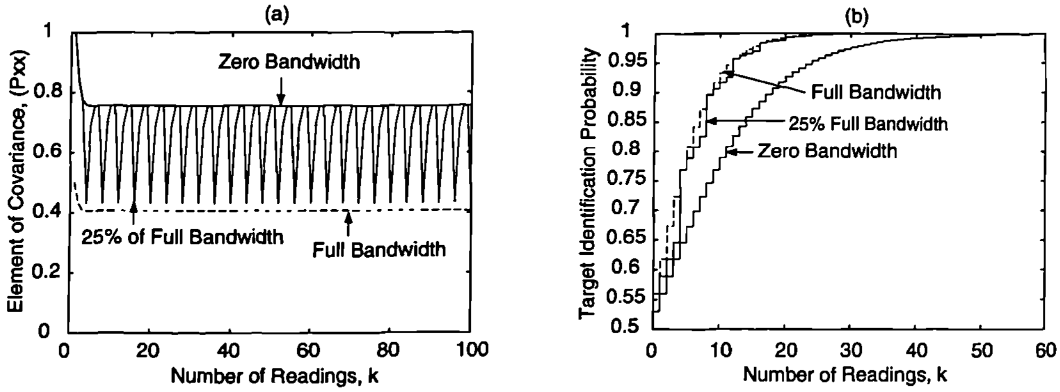


Figure 5.7: Bandwidth constrained (a) tracking and (b) identification estimators.

The variance of the position estimate for the full bandwidth estimation is less than that for the zero bandwidth case. For the 25% of full bandwidth results the following observations are made:

1. When a communication is received by the platform the variance of the estimate drops towards the full bandwidth result, but does not obtain this minimum value.

2. During the time steps following a communication the variance gradually increases in value until it reaches the maximum variance given by the zero bandwidth results.

The time constants for the reduction and increase in variance will be dependent on the process and observation noise levels. Further, the communications bandwidth allocation also affects the variance. Therefore, in multi-target environments the management of the constrained bandwidth can change the system performance. This motivates communications management to achieve some system level performance, i.e. maximising overall track certainty.

The time for the identification estimator's target probability to converge is longer for the zero bandwidth example than for the full bandwidth implementation. For the 25% of full bandwidth results the following observations are made:

1. When a communication is received by the platform the target probability is raised to the full bandwidth level.

2. During the time steps following a communication the target probability deviates away from that of the full bandwidth implementation towards that of the zero bandwidth.

Again, the higher the communications bandwidth the better the identification performance. Therefore, in multi-target scenarios the allocation of bandwidth is important in obtaining some system level criterion, i.e. minimising the identification times. This can be achieved using communications management.

It should be noted that a communication on target identification has a greater influence on the estimator performance than for a tracking filter. This situation arises since the contribution of a communication for the identification estimator is not degraded by process noise (or a prediction stage) as is the case for the tracking filter, since we assume a target's identity does not change with time.

This simple example shows that the level of communications bandwidth allocated to an estimator influences its performance. For the tracking estimator the higher the communications bandwidth allocation the greater the certainty associated with the track. For the identification estimator the higher the communications bandwidth allocation the shorter the identification time to reach a certain level of identification probability.

This section has answered the question 'how can the channel filter be implemented and how does it affect the tracking and identification estimators?' The update methods for the channel and global filters have been considered. This showed that for consistency, the filter's update times should be synchronised. In addition, the effects of implementing the channel filter in bandwidth limited systems has been investigated. In essence, this indicates that the higher the communications bandwidth the better the track and identification performance. For a multi-target scenario this motivates the use of communications management. This is discussed next.

5.4 Communications Management Implementation

Here we answer the question 'how can communications management be implemented in the context of this thesis?' This is achieved by considering the communications management infrastructure and algorithms.

5.4.1 Communications Management Infrastructure

The aim of the communications management algorithm described in this thesis is for the transmitting platform to decide what information, i.e. on what targets, it will communicate during its communication time slots.

For the research presented in this dissertation the order of the communications time slots are fixed with the sequence comprising each platform in turn. Further, the transmitting platform communicates the same data to each platform. This provides a broadcast communication. However, a similar approach could be applied for transmitting data on different targets too different platforms. This would require a bank of global filters for each communication link.

The topology of the system is shown in Figure 5.8. Here the processing on the platform comprises global filters, channel filters and a communications management decision algorithm. The tracking and identification algorithms employed in the investigation system are as stated in Chapter 3 for multi-platform and multi-target scenarios.

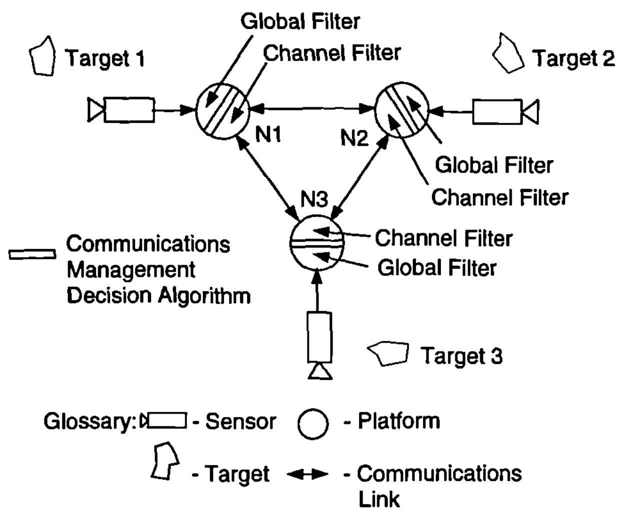


Figure 5.8: Investigation system infrastructure.

Hence, at the end of an update each platform has the following data available:

	Track	Identification
Global Data	${}^t\tilde{\mathbf{y}}_i(k\|k)$	
	${}^t\tilde{\mathbf{Y}}_i(k\|k)$	${}^tP_i(\mathbf{X}\|\mathbf{Z}^k)$
Channel Data	${}^t\tilde{\mathbf{y}}_{ij}(k\|k)$	
	${}^t\tilde{\mathbf{Y}}_{ij}(k\|k)$	${}^tP_{ij}(\mathbf{Z}^k\|\mathbf{X})$
Data for Tx	${}^t\mathbf{m}_{ij}(k)$	
	${}^t\mathbf{M}_{ij}(k)$	${}^tP_{ij}(\mathbf{Z}^{*k}\|\mathbf{X})$

$\forall t \in \mathbf{T} = \{1 \dots T\}$, $\forall i \in \mathbf{N} = \{1 \dots N\}$, and $\forall j \in \mathbf{N}$ where T is the number of targets and N is the number of platforms in the scenario. These are used in the communications management algorithm, along with a prediction of the information state of the other platforms, to decide which data to transmit.

5.4.2 Decision Algorithm

An information theoretic approach is used to maximise the change in absolute posterior entropic information gain, over a single broadcast transmission, see Chapter 4. Here, the choice of what data to communicate is made by the *transmitter*. A schematic of the algorithm is provided in Figure 5.9.

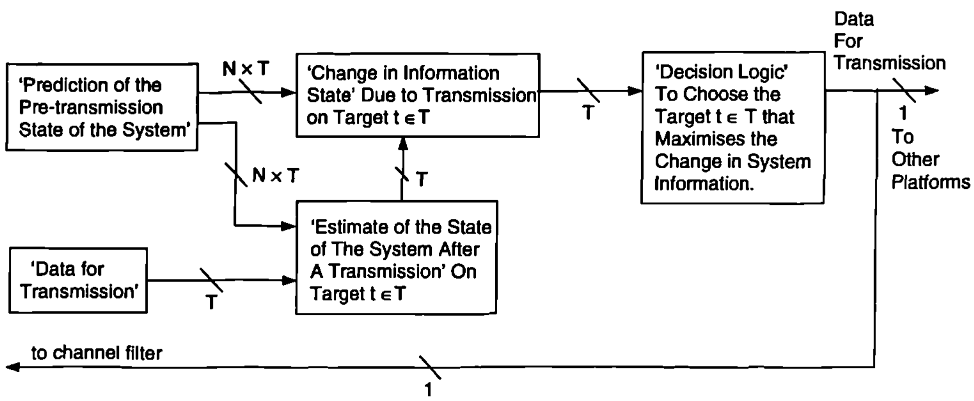


Figure 5.9: Communications management decision algorithm.

Its application for the management of communications of tracking and identification estimates are now discussed.

Tracking Decisions

Here the 'Prediction of the Pre-transmission State of the System' process provides a prediction of the current uncertainty of *each* target state estimate at *each* platform. Therefore, $N \times T$ target predictions are produced. For the tracking estimator these are denoted by the covariances as:

$$ {}^{t}\hat{\mathbf{P}}_i(k^+|k^-) = {}^{t}\hat{\mathbf{P}}_i(k^-|k^-) \quad \forall i \in \mathbf{N} \text{ and } \forall t \in \mathbf{T} \tag{5.14} $$

where the $-$ indicates a pre-transmission state and the $+$ indicates a post transmission state. These predictions can be based on a number of ideas, the most promising being modelling techniques (Noonan 1996)[2]. The set of predicted values are passed to the 'Estimate of the State of the System After a Transmission' and the 'Change in Information State' processes.

The 'Estimate of the State of the System After a Transmission' combines the predicted values with the 'Data for Transmission' such that the effect on the total system information due to a communication can be estimated. Data communicated on each target, $c \in \mathbf{T}$, from the transmitting platform, $o \in \mathbf{N}$, is considered in turn. Hence the following estimates are calculated:

$$ {}^{c}\tilde{\mathbf{P}}_i^{-1}(k^+|k^+) = {}^{c}\hat{\mathbf{P}}_i^{-1}(k^+|k^-) + {}^{c}\mathbf{M}_{ij}(k) \quad \forall i \in \mathbf{N}, i \neq o, \tag{5.15} $$

and

$$ {}^{c}\tilde{\mathbf{P}}_i^{-1}(k^+|k^+) = {}^{c}\hat{\mathbf{P}}_i^{-1}(k^+|k^-) \quad i = o. \tag{5.16} $$

These values are then employed by the 'Change in Information State' to calculate the absolute posterior entropic information gain due to a communication:

$$ {}^{c}I_{as}^{Tr}(k) = -\frac{1}{2}\ln[\sum_{\forall i \in \mathbf{N}} \sum_{\forall t \in \mathbf{T}} |{}^{t}\tilde{\mathbf{P}}_i(k^+|k^+)|] + \frac{1}{2}\ln[\sum_{\forall i \in \mathbf{N}} \sum_{\forall t \in \mathbf{T}} |{}^{t}\tilde{\mathbf{P}}_i(k^-|k^-)|] \tag{5.17} $$

where

$$ {}^{t}\tilde{\mathbf{P}}_i^{-1}(k^+|k^+) = {}^{t}\hat{\mathbf{P}}_i^{-1}(k^+|k^-) \quad \forall i \in \mathbf{N} \text{ and } \forall t \in \mathbf{T}, t \neq c\ . \tag{5.18} $$

This results in T values, i.e. $\forall c \in \mathbf{T}$, which are passed to the 'Decision Logic' process. These values are represented in Figure 5.10.

The 'Decision Logic' process selects the target that has the largest predicted absolute posterior entropic information gain, i.e.

$$ C_{\text{trans}} = \arg\max_{c}[{}^{c}I_{as}^{Tr}(k)]. \tag{5.19} $$

Data on this target are then transmitted to the other platforms. These are also used to update the channel filter.

[2]These may use the global and/or channel data as the basis for their predictions.

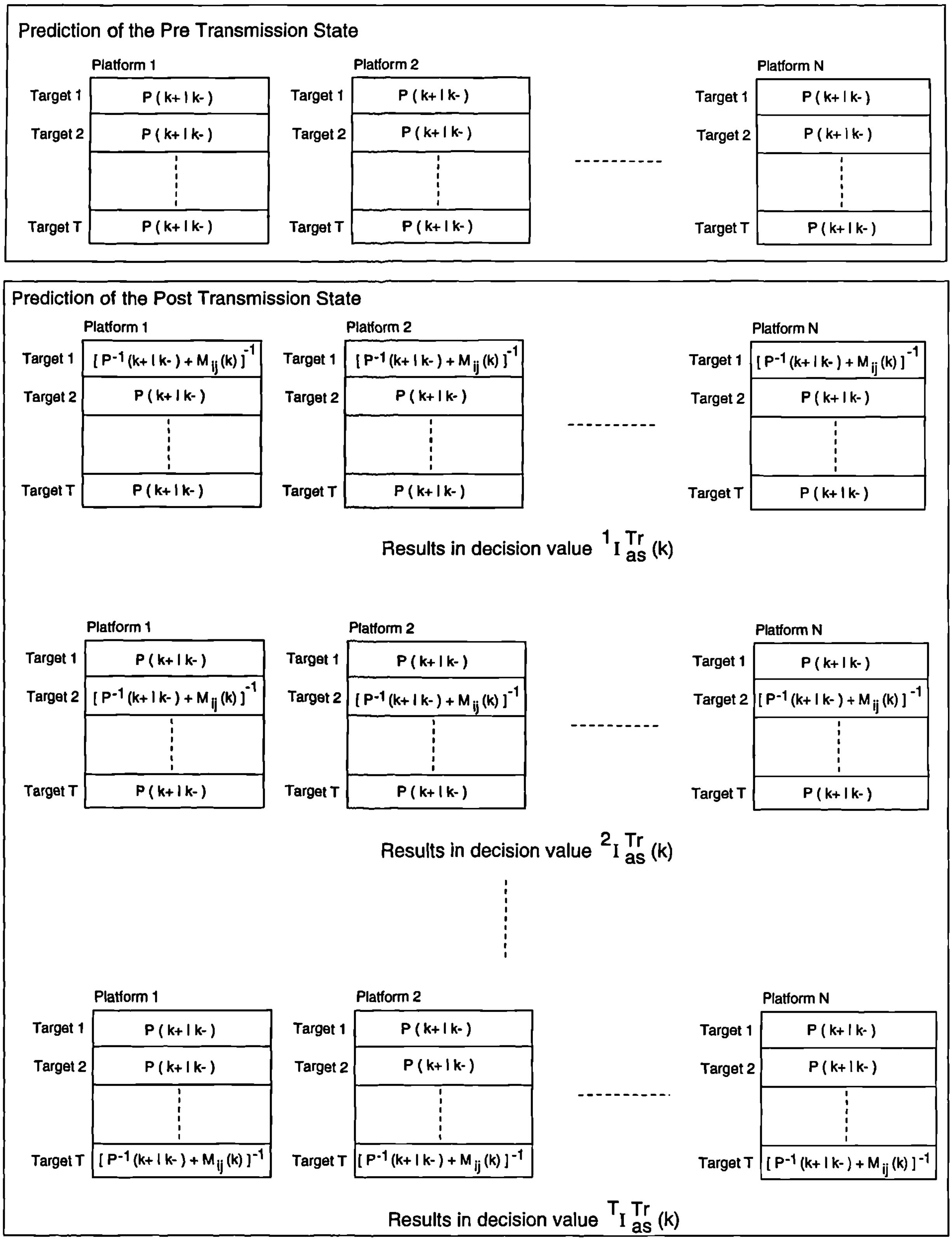


Figure 5.10: Generation of the track decision values, see text for details.

Identification Decisions

Now the decision algorithm schematically shown in Figure 5.9 is applied to an identification estimator. Here the 'Prediction of the Pre-transmission State of the System' process provides a prediction of the current uncertainty of *each* target identity estimate at *each* platform. Again there are T targets and N platforms in the system. Therefore, $N \times T$ target predictions are produced. For the identification estimator these are denoted by probability vectors:

$$ {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k-}) \quad \forall i \in \mathbf{N} \text{ and } \forall t \in \mathbf{T}. \tag{5.20} $$

Again, these predictions can be based on a number of ideas (Noonan 1996), e.g. system modelling. The set of predicted values are passed to two other processes, the 'Estimate of the State of the System After a Transmission' and the 'Change in Information State'.

The 'Estimate of the State of the System After a Transmission' combines the predicted values with the 'Data for Transmission' such that the effect on the total system information due to a communication can be estimated. Data communicated on each target, $c \in \mathbf{T}$, from platform, $o \in \mathbf{N}$, is considered in-turn. Hence the following estimates are calculated:

$$ {}^{c}P_i(\mathbf{X}|\mathbf{Z}^{k+}) = {}^{c}P_i(\mathbf{X}|\mathbf{Z}^{k-}) \times {}^{c}P_{ij}(\mathbf{X}|\mathbf{Z}^{*k}) \times \alpha \quad \forall i \in \mathbf{N}, i \neq o, \tag{5.21} $$

and

$$ {}^{c}P_i(\mathbf{X}|\mathbf{Z}^{k+}) = {}^{c}P_i(\mathbf{X}|\mathbf{Z}^{k-}) \quad i = o. \tag{5.22} $$

These values are then employed by the 'Change in Information State' to calculate the absolute posterior information change due to a communication, see Figure 5.11 and Equation 5.23:

$$ {}^{c}I^{Id}_{as}(k) = \sum_{\forall_{i \in \mathbf{N}}} \sum_{\forall_{t \in \mathbf{T}}} {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k+}) \ln {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k+}) - \sum_{\forall_{i \in \mathbf{N}}} \sum_{\forall_{t \in \mathbf{T}}} {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k-}) \ln {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k-}) \tag{5.23} $$

where

$$ {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k+}) = {}^{t}P_i(\mathbf{X}|\mathbf{Z}^{k-}) \quad \forall i \in \mathbf{N} \text{ and } \forall t \in \mathbf{T}, t \neq c\ . \tag{5.24} $$

This again results in N values, i.e. $\forall c \in \mathbf{N}$, which are passed to the 'Decision Logic' process. This process selects the item that has the largest predicted absolute posterior entropic information gain, i.e.

$$ C_{\text{trans}} = \arg\max_{c}[{}^{c}I^{Id}_{as}(k)] \tag{5.25} $$

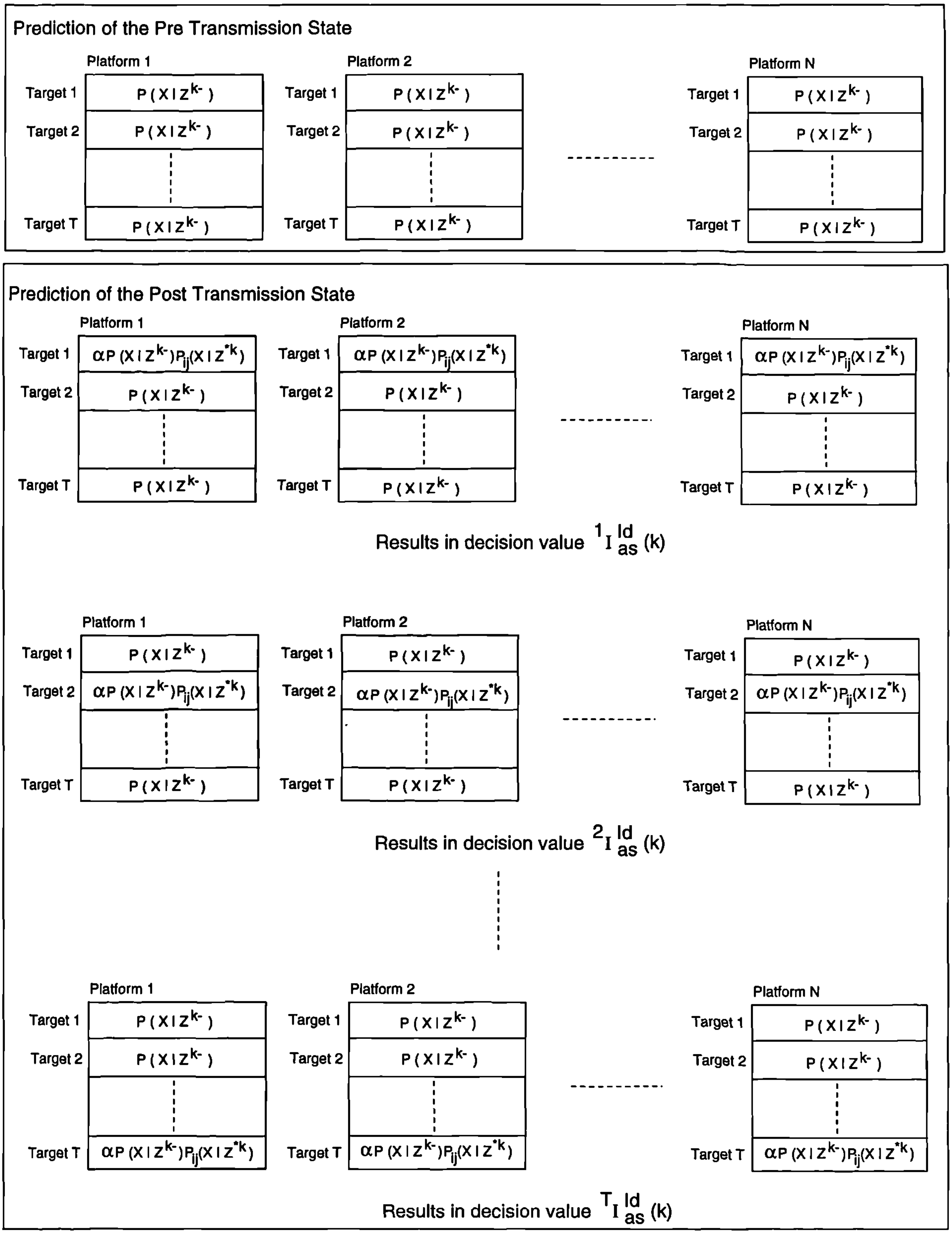


Figure 5.11: Generation of the identification decision values, see text for details.

and data on this target are then transmitted to the other platforms. These values are also used to update the channel filter.

It should be noted that if data on more than one target is to be transmitted the 'Decision Logic' process lists the predicted absolute posterior entropic information gain values in descending order. Target data is then selected for an appropriate number from the top of that list.

Further, the predicted absolute posterior entropic information gain values for track and identification can be combined to provide a target level value, see Section 4.5.1.

This section has answered the question 'how can communications management be implemented in the context of this thesis?' This has been achieved by considering the communications management infrastructure and management algorithms. These comprise three elements: global filters, channel filters and a communications management decision algorithm. The functionality of the global and channel filters have already been discussed. Here a detailed description of the communications management decision algorithm has been provided.

5.5 Performance Metrics and the Trade-off Concept

This section aims to answer the question 'how will system performance be measured and trade-off potential determined?' This is achieved by considering suitable performance metrics for developing process models and applying these to investigate trade-off potential.

5.5.1 Performance Metrics

Here track and identification performance data are considered. Further, their application to the development of process models is described.

Dealing with Fluctuations

For a bandwidth limited system, the track and identification performance can have associated fluctuations. These are brought about by two effects. Firstly, the communications protocol introduces *systematic fluctuations* - refer back to Section 5.3.3 and Figure 5.7. Secondly, fluctuations can be caused due to a number of *random influences.* For example, the imperfect nature of the sensor means it will sometimes fail to 'see' the target although it is within its field of view, i.e. it has an associated probability of detection, $P_d < 1$. This effect often occurs randomly. An imperfect communication system also introduces randomness into the system. This is related to failures in the transmit and receive processes and random influences on the communications management algorithm. Therefore, in order to overcome this random component Monte Carlo simulations will be employed.

Tracking Performance Data

The uncertainty associated with a track estimate is represented by the covariance matrix. Different metrics from the covariance can be employed for analysis purposes. These include individual matrix elements, and the trace or determinant of the covariance. For the work presented in this thesis the determinant is employed since it encompasses the overall 'volume' of uncertainty associated with the covariance.

For a multi-platform and multi-target simulation, at each time step, determinant values will be generated for *each* target on *each* platform. At these time steps intuitive performance metrics are the *average* and *maximum* values of the determinants. Further, for a complete 'run', over a number of time steps, it is intuitive to take the average of these *average* and *maximum* values. Hence, for M Monte Carlo simulations, M analysis values are produced for the average and maximum results.

Identification Performance Data

The certainty associated with an identification estimate is represented within the posterior probability identity vector. Different metrics can be employed for this analysis purpose. These include those based on individual elements or combinations of the elements of the vector, e.g. entropy. For the work documented in this thesis, the probability element associated with the most likely target type is employed. This is common practice in the data fusion community (Deaves and Greenway 1994b).

For a bandwidth limited system the profile of the identity probability elements of the vector can have associated steps in the profile. As for the tracking data these are influenced by systematic effects, see Figure 5.7(b), and the same random effects as those discussed for track performance data. Hence, again Monte Carlo simulations are applied to average out the random effects.

An intuitively important metric for an identification system is the time it takes the estimator to reach a particular probability threshold, e.g. the time it takes to reach a probability of 0.8 that a target is of a certain type. For a multi-platform and multi-target simulation, identity times will be produced for *each* target on *each* platform. Therefore, from these values useful statistical data are the *average* and *maximum* identification times. Hence, for M Monte Carlo simulations M analysis values for the average and maximum results are generated.

Process Models

The results produced from the thesis investigation are represented as process models which relate the system performance metric, based on track or identification, to the inter-nodal communications bandwidth. In order to produce these plots, the Monte Carlo simulation results have to be summarised. Several methods exist for this purpose. Here three are briefly described with their merits and drawbacks stated:

1. **Common Profile Representation:** In this method of representing Monte Carlo simulations a frequency of occurrence profile is plotted. It is then analysed to determine if it is a common profile, e.g. Gaussian or binomial. If this is the case then simple equations can be employed to determine the mean and standard deviation for all the results. A cut-off point, for say 90% of the distribution, can then be determined to provide the 90 percentile.

   This method is computationally in-expensive and can usually be calculated 'on-the-fly' (once an inspection has been carried-out). However, the results produced may be prone to large errors.

2. **Counting Method for Profile Representation:** In this method of representing Monte Carlo simulations the values are sorted into order. A count is then made of a proportion of the results, e.g. 90%. This provides the 90 percentile on the values obtained. The result of this method is represented in Figure 5.12.

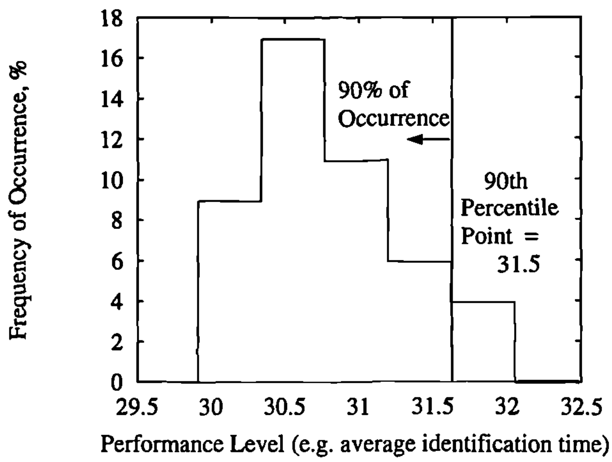


Figure 5.12: The 'counting' method for evaluating distributions.

This method has the advantage of being more accurate than the first method especially if the profiles are not of a common type. However, this method (generally) requires off-line processing.

3. **Curve Fitting for Profile Representation:** In this method a curve is fitted to the profile of the Monte Carlo simulation results such that some criteria is met, e.g. a χ^2 square test is maximised. A statistical analysis of the curve, not the results, is then carried out to determine a percentile, say 90th.

   This method has the advantage of being more accurate than the first and second methods. However, this method can be time consuming and computationally expensive to implement.

In order to produce process models a confidence interval is required on the percentile point. This is achieved by carrying out the simulation a number of times and calculating the *standard error of the individual simulation* (Squires 1993).

When percentile points and their associated standard error have been obtained for a number of inter-platform communications bandwidths a performance process model can be plotted. A representative example is provided in Figure 5.13.

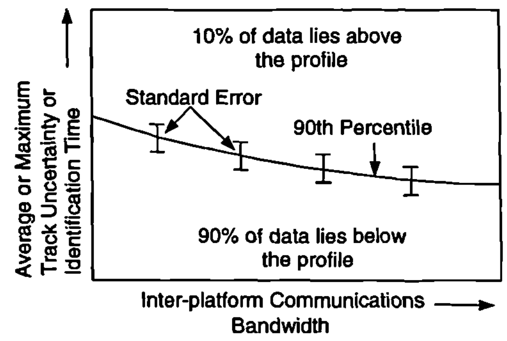


Figure 5.13: Performance process model.

Although both average and maximum values are suitable performance metrics only the *average* results are considered in this thesis. This is motivated on the basis that the aims of the evaluation and application propositions are only to *demonstrate an effect.* This can be achieved by considering a single performance metric alone.

In this section system level performance metrics were discussed. These are based on track and identification metrics. The track metric is derived from the determinant of the covariance matrix, whereas the identification metric is derived from the time taken to reach a threshold probability value. Monte Carlo simulations are employed to represent the effect of randomness in the simulations. Further, these are processed to determine the 90th percentiles with their associated standard errors, to produce process models that relate *average* performance to inter-platform bandwidth.

5.5.2 The Trade-off Concept

Trade-offs identified during the design stage of a system provide the potential for delivering cost effective solutions to the customer's requirements. This idea is clarified with a simple example:

Consider the design of a simplified hypothetical decentralised sensing system. Here the designer has two different sensor types, high and low performance, and two types of communications systems, again high and low performance, that can be employed in the solution. The assumption is made that a high performance components are more expensive than the low performance components. For this simplified design four choices are available: (i) high performance communication system and sensor type (C=H, S=H), (ii) high performance communication system and low performance sensor (C=H, S=L), (iii) low performance communication system and high performance sensor (C=L, S=H), and (iv) low performance communications system and sensor types (C=L, S=L). These are represented on the example process model of Figure 5.14 where the x axis gives the inter-platform communications bandwidth and the y axis gives a system performance metric for track uncertainty.

Let's assume that three customer's wish to purchase the system: customer A requires a low performance system, customer B requires a high performance system and customer C requires a medium performance system. These performance levels are represented on Figure 5.14 as horizontal lines. Any system whose performance lies below the line meets the customer's specification. Those above it fail to meet the requirements.

Therefore, for a low performance system all four possible designs meet the specification. Hence, a system comprising low performance communications systems and sensor types are provided for customer A as this is the cheapest design. For a high performance system only the high performance communication systems and sensor types design meets the specification. Hence, customer B is provided with that design. The medium performance system can be achieved using one of three designs. However, the cheapest design will be either (S=H, C=L) or (S=L, C=H).

This simple example demonstrates that trade-off options *can* exist during the system design stage. However, these trade-off options are restricted by the customers requirements and the performance of the available system components.

Evaluating such trade-offs may not be possible (or feasible) by combining the components of a system and testing it out for 'real'. This is particularly true for complex systems. For example, consider a system comprising of 10 components each with three available types. In this example $59,049$, i.e. 3^{10}, possible combinations exist. In order to evaluate each of these, analytical or simulation methods are required. However, often analytical techniques are difficult to set-up for complex systems. This leaves simulation

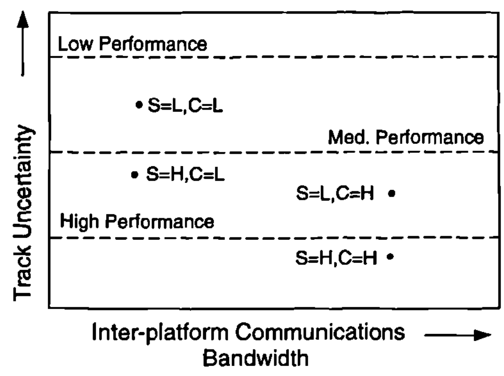


Figure 5.14: Example process model.

as the only feasible alternative. This is an area investigated by the thesis.

This section has answered the question 'how will system performance be measured and trade-off potential determined?' This has been achieved by stating the performance metrics that will be used in the thesis. These will be based on *average* values for the determinant of the track covariance and identification time to reach a pre-defined threshold. Further, process models will be developed which represent the relationship between track and identification performance with the inter-platform communications bandwidth. These will be used to investigate trade-off issues as demonstrated by the example provided.

5.6 Communications Management Evaluation

This section of the thesis aims to answer the question 'how can communications management be evaluated in the context of this thesis?' This is achieved by developing a number of hypotheses which when tested lend support to the proposition:

Proposition 1: Evaluation of Communications Management.
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides a measurable increase in performance when compared with ad-hoc approaches.'

5.6.1 Evaluation Hypothesis, H1: Individual management

In this section a hypothesis is stated which compares the performance of the track and identification based communications management algorithm with that of an ad-hoc algorithm.

The ad-hoc algorithm employed is based on a *round-robin* approach. This has been chosen since it is an intuitive 'fair-play' algorithm. Further, it provides the following characteristics:

1. **Complete:** This algorithm ensures that each platform communicates data on each target.

2. **Unbiased:** The algorithm ensures that each platform allocates an equal proportion of communications bandwidth to each target.

3. **Efficient:** The algorithm is computationally cheap to implement, i.e. it only involves incrementing a pointer after the algorithm has been initialised.

However, the solution is sub-optimal when compared with the *perfect information* implementation of the information based algorithm. In this situation, the information based algorithm will always select the correct data to communicate whereas the round-robin algorithm has a discrete probability of $1/T$ of choosing the correct data.

The implementation details of the round-robin algorithm employed in this thesis are now provided: Each platform produces a random communications sequence for the targets. These are stored in a list during the simulation initialisation. Each platform maintains a round-robin communications management pointer to the list. This is incremented after each transmission. When the end of the list is reached the pointer is reset.

For the evaluation investigations, process models with two performance profiles are produced. One represents the information based communications management algorithm. The other is generated from the round-robin result. The hypothesis developed is used to determine if there is *any* benefit to employing an information based algorithm when compared with a round-robin algorithm. This hypothesis is stated as:

> **Evaluation Hypothesis H1:** Individual management.
> 'An information theoretic approach to communications management, based on track or identification information, never provides a measurable increase in performance when compared with a round-robin approach.'

5.6.2 Evaluation Hypothesis, H2: Combined management

Here a hypothesis is stated which compares the performance of a communications management algorithm based on the combination of track and identification information with that of a round-robin approach.

Again, process models which employ two performance profiles are produced. One representing the information based algorithm the other the round-robin approach. The hypothesis is used to determine if there is any benefit to employing a combined information based algorithm when compared with a round-robin algorithm. This hypothesis is stated as:

> **Evaluation Hypothesis H2:** Combined management.
> 'A combined decision metric, based on track and identification information, never provides a measurable increase in performance when compared with a round-robin approach.'

This management scheme is based on the linear combination of the posterior entropic information gain of track and identification data, see Equations 4.57, 5.19 and 5.25.

5.6.3 Evaluation Hypothesis, H3: Scenario dependence

Next a hypothesis is stated which compares the performance of the combined communications management algorithm with that of a round-robin algorithm operating under different target scenarios.

Again, process models which employ two performance profiles are produced; one representing the information based algorithm the other the round-robin approach. The hypothesis developed is used to determine if there is ever any benefit to employing an information based algorithm when compared with a round-robin algorithm for scenarios when all the targets have very similar or dissimilar characteristics. This hypothesis is stated as:

> **Evaluation Hypothesis H3:** Scenario dependence.
> 'A combined decision metric, based on track and identification information, does not provide a measurable benefit, even for scenarios where the targets have different track and identification characteristics.'

> This section has answered the question 'how can communications management be evaluated in the context of this thesis?' This was achieved by stating three hypotheses concerned with evaluating information based communications management when compared with an ad-hoc, i.e. round-robin, approach. These are (H1) individual management, (H2) combined management, and (H3) scenario dependence. The *testing* of these hypotheses will lend support to the thesis *evaluation* proposition, i.e. **Proposition 1.**

5.7 Communications Management Application

This section of the thesis aims to answer the question 'how can communications management be applied in the context of this thesis?' This is achieved by considering the trade-off potential available in the design of avionic systems. Again a number of hypotheses are developed which when *tested* lend support to the proposition:

> **Proposition 2:** Application of Communications Management.
> 'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides the potential for trade-offs to be made/evaluated/calculated between the performance of the communications system and other resources.'

5.7.1 Application Hypothesis, H4: Processor trade-off

The performance of a processor is characterised here by the accuracy with which it can estimate the communications management decision values. The higher the processor computational power the higher its estimation accuracy. The hypothesis is stated as:

> **Application Hypothesis H4:** Processor trade-off.
> 'An information theoretic approach to communications management never provides the potential for trade-off between the communication system and processor.'

5.7.2 Application Hypothesis, H5: Sensor trade-off

The performance of the sensor is characterised here by the accuracy with which its observation can locate and identify the targets. The higher the sensor performance the higher its observation accuracy. The hypothesis is stated as:

> **Application Hypothesis H5:** Sensor trade-off.
> 'An information theoretic approach to communications management never provides the potential for trade-off between the communication system and sensor.'

5.7.3 Application Hypothesis, H6: Platform number trade-off

Next a hypothesis is stated which implies that a trade-off potential does not exist between the number of platforms and the performance of the inter-platform communications system. The hypothesis is stated as:

Application Hypothesis H6: Platform number trade-off.
'An information theoretic approach to communications management never provides the potential for trade-off between the communication system and number of platforms.'

5.7.4 Application Hypothesis, H7: Multi-resource trade-off

Finally a hypothesis is stated which implies that a trade-off potential does not exist between the processor, sensor, number of platforms and the performance of the inter-platform communications system to meet a given system requirement. The hypothesis is stated as:

Application Hypothesis H7: Multi-resource trade-off.
'An information theoretic approach to communications management never provides the potential for trade-off between the processor, sensor, number of platforms and communication system.'

Such trade-off issues are critical when achieving cost effective avionic designs.

This section has answered the question 'how can communications management be applied in the context of this thesis?' This has been achieved by stating four hypothesis. The first three are concerned with the trade-off potential between the processor, sensor, number of platforms and the communication system, i.e. H4, H5, H6 respectively. The forth, i.e. H7, is concerned with achieving an avionic system design employing all the system resources collectively. The *testing* of these hypotheses will lend support to the thesis *application* proposition, i.e. **Proposition 2.**

5.8 Summary and Concluding Remarks

This chapter of the dissertation has been concerned with communications management in decentralised systems. The aim of the chapter was to answer the question 'how will communications management be implemented, evaluated and applied in the context of this thesis?' This has been achieved through the sections of the chapter.

A review of decentralised sensing systems resources and their management has been provided. This places communications management in context with other resource management issues in decentralised systems. Further, the review highlights resources to be considered as part of the communications management *application* investigation.

The details provided through considering the channel filter implementation, communications management implementation and performance metrics and trade-off concepts, along with the thesis requirements (Chapter 2), infrastructure capabilities (Chapter 3) and management capabilities (Chapter 4) provide the *Test-bed Capability* for the thesis.

Three hypothesis, i.e. H1, H2 and H3, have been stated which when tested will lend support to the *evaluation* proposition of the thesis, i.e. **Proposition 1**: that an information theoretic approach to communications management can improve system performance.

Four hypothesis, i.e. H4, H5, H6 and H7, have been stated which when tested will lend support to the *application* proposition of the thesis, i.e. **Proposition 2**: that the same approach can enable effective system design trade-offs.

Chapter 6

Decentralised Multi-Platform Multi-Target Simulator

6.1 Introduction

The aim of this chapter is to answer the question '*How* will the communications management evaluation and application hypotheses be tested?' This knowledge is then applied to test the appropriate hypotheses.

The mapping between these questions and sections of the chapter are provided in Figure 6.1. Section 6.2 provides a brief justification on employing a simulator to generate the results for the thesis. The decentralised multi-platform multi-target simulator is described in Section 6.3. The configuration of the platforms and targets are provided in Section 6.4. This is followed by the thesis test scenarios relating to the *evaluation* and *application* hypotheses, in Sections 6.5 and 6.6 respectively. Section 6.7 provides details of the system level performance metrics employed in the thesis. This chapter concludes with a summary and some concluding remarks in Section 6.8.

6.2 Simulation Justification

This section of the chapter aims to answer the question 'how was the simulation approach justified for the investigation?' This is achieved by considering the merits of both simulation and 'real' data analysis.

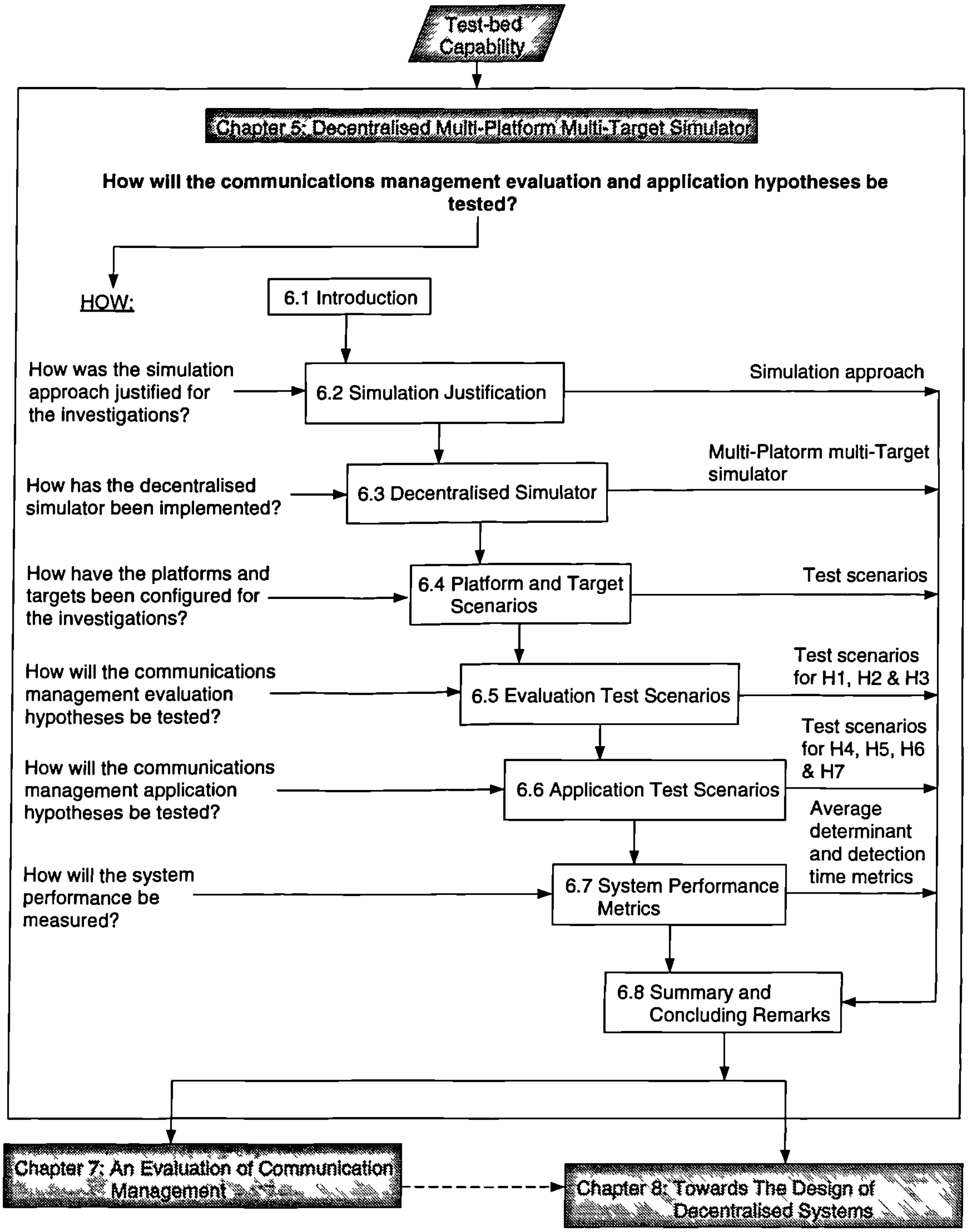


Figure 6.1: Reader's map for Chapter 6.

6.2.1 The Merits of Simulation Analysis

Simulation can provide a relatively cheap and quick method for analysing system performance. This is especially true for multi-platform and multi-target systems where 'real' component costs are high. Further, multiple 'runs' or Monte Carlo simulations are easily set-up and produce results relatively quickly. Such simulations are difficult for real systems since making the platforms and targets repeat runs accurately may not be feasible. Further, even if the real system is repeatable it may be time consuming to carry out.

In this thesis a battlespace scenario is investigated. The cost of employing real aircraft to produce Monte Carlo simulations would be extremely expensive.

6.2.2 The Merits of Real Data Analysis

Real data analysis provide the advantages that all system effects are present. For simulations some important system issues may be overlooked. Hence their effect on the simulated system will not occur. This could lead to a completely inaccurate set of results being produced and analysed. Further, carrying out real data tests gives the customer an increased confidence in the product.

6.2.3 Simulation versus Real Data

A comparison of simulation and real data tests shows that there are advantages and disadvantages for both methods. Hence, their use will be heavily dependent on the application. Further, the methods should not be viewed as exclusively independent for the task of analysis.

This section has answered the question 'how was the simulation approach justified for the investigations?' Given that this thesis is concerned with a battlespace scenario the most feasible analysis, at this stage of the research, is through simulation.

6.3 Decentralised Simulator

Here we aim to answer the question 'how was the decentralised simulator implemented?' This is achieved by documenting the structure of the decentralised multi-platform multi-target simulator used for the thesis investigations.

6.3.1 Overview

An overview of the simulator design is represented in Figure 6.2 (Durrant-Whyte et al. 1998, Sutcliffe et al. 1997). The system comprises of three main modules. These are the World Module, the Platform Module and the Communications Model Module. The World Module generates all the target and platform trajectories. These data are passed to all the Platform Modules for data fusion processing. Further, the multi-platform simulator allows inter-platform communication through the Communications Module.

The feedback line marked A can be used to incorporate targets that react to the platform positions. For the work presented here, this function is 'hand crafted' in that the target and platform trajectories are programmed prior to code compilation.

The feedback line marked B is used to provide the Communications Model Module with transmission characteristics. For example, the probability of a communication being successful between a pair of platforms could be made a function of their distances apart, enemy jamming capabilities or inter-platform terrain. A simplified implementation is employed here.

The individual modules are discussed below.

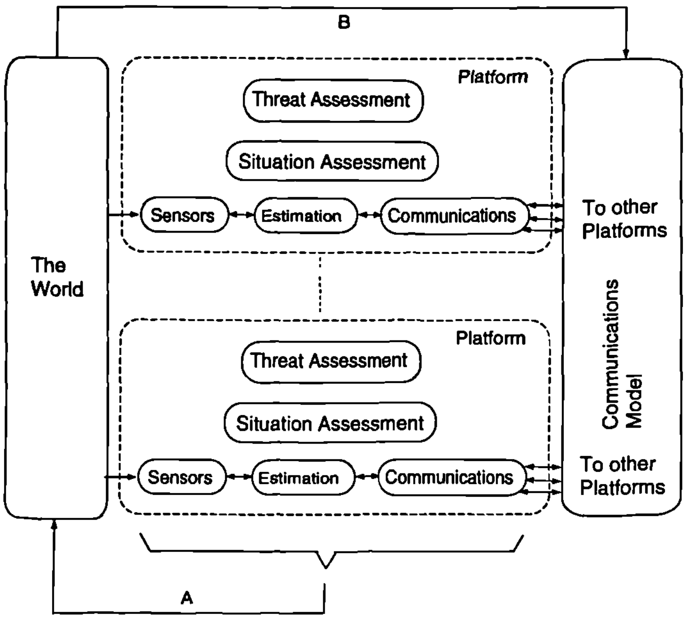


Figure 6.2: Components in a Decentralised Tracking System

6.3.2 World Module

This module produces the flight trajectories for the simulation targets and platforms. The exact number of targets/platforms, their types, and trajectories are programmed and set prior to code compilation.

Complete trajectories for all targets and platforms for the complete run are calculated before the data fusion simulation begins. These data are made available to the Platform Module as required.

6.3.3 Platform Module

The platform module comprises five processes.

Sensor Process

This process takes as its input the platform/target positions from the World Module. These data allow the sensor process to determine the noise level appropriate to an individual observation. This simulation noise is dependent on the distance between the platform and target.

Figure 6.3 represents the sensor process models for the tracking simulation. Here sensor variance is plotted against the platform-to-target distance. The simulator allows the maximum variance, minimum variance and sensor range to be set before compile time. It should be noticed that the sensor variance is related to the platform-to-target distance, r_g, as $1/r_g^4$. This is intended to be similar to the relationship that exists for a radar. When the target moves beyond the range of the platform, the sensor variance is set to infinity. Three sensors of different performance characteristics are employed. These are referred to as high, medium and low performance sensor types, see Figure 6.3.

Figure 6.4 represents the degradation in the performance of the identification sensor as the platform-to-target distance is increased. This variation is provided by firstly setting a base likelihood value $P_b(Z(k)|\mathbf{X})$ before code compilation. This value is then varied with a *linear power* relationship to produce the observation likelihood, $P_o(Z(k)|\mathbf{X})$:

$$P_o(Z(k)|\mathbf{X}) = \alpha P_b(Z(k)|\mathbf{X})^{f(r_g)} \tag{6.1}$$

where α is a normalising constant. This relationship is such that increasing the platform-to-target distance, r_g, increases the observation likelihood uncertainty. On Figure 6.4 the largest element in the observation likelihood vector is plotted against the platform-to-target distance. Here, platform-to-target distances larger than the sensor range result in a probability of $1/n$, where n is the number of target types. This indicates

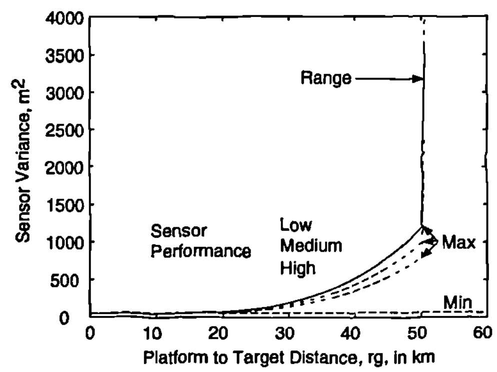


Figure 6.3: Sensor variance against platform-to-target distance used in the thesis investigations.

that the observation likelihood vector then takes on its *least informative value.* As this distance decreases, the probability increases. This relationship is intended only to roughly mimic a 'real' sensor in the sense that the closer the target is to the sensing platform the better that sensor can identify it. Three sensors of different performance characteristics are employed. These are again referred to as high, medium and low performance sensor types. The effect of employing a different sensor type to observe the three different types of target, i.e. bomber, fighter and advanced fighter, are represented in Figure 6.4. It should be noted that the bomber target is easier to identify than the fighter, which itself is easier to identify than the advanced fighter[1].

Further, each target has an associated probability of detection, P_d, drawn from a 'flat' distribution. For the results presented later in the thesis, the bomber, fighter and advanced fighters have P_d values of of 0.9, 0.85 and 0.8 respectively. The sensor update interval is fixed for all aircraft at a value of 0.5 s.

Estimation Process

The estimation process maintains a global estimate of each target's identification and track. Here information generated by the sensor, or received from other platforms via a communication, are used to recursively update the global estimates.

The first stage of the estimation process is to perform a data association function. For this simulation, the data association is kept very simple and involves only the gating and observation (or track) to track assignment processes. This is achieved using a simple nearest neighbour data association algorithm (Bar-Shalom and Fortmann 1988). Track

[1]Note the different y axes scales.

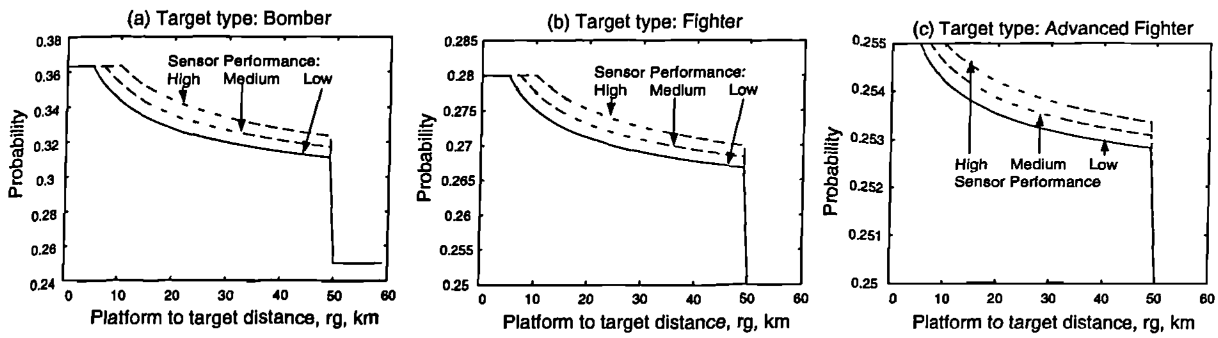


Figure 6.4: Target probability against platform to target distance used in the thesis.

initiation and reaping are not considered here. When the data association is complete, each track filter and identity estimate are updated using the appropriate equations. These are provided in Section 5.4.1.

In the thesis investigations, constant velocity tracking models are applied to track all the targets. However, the targets do manoeuvre. A method of process model switching (Bar-Shalom and Fortmann 1988) is employed to account for the increased uncertainty in target location. Here two different process noise variances are used, one appropriate for when the target is moving with (approximately) constant velocity, and another (larger) value appropriate to when the target performs a manoeuvre. A problem with this approach is detecting when to apply the different models. This can be overcome by analysing the innovation sequence (Bar-Shalom and Fortmann 1988). However, for simplicity, in the simulator employed for this work the models are switched at precisely the right time using the exact target trajectory information from the World Module. From (Bar-Shalom and Li 1993), the process noise standard deviation should lie between $0.5a_v$ and a_v, where a_v is the maximum acceleration of the target. When the target moves with constant velocity the process noise variance is set to a value of $200m^2$, i.e. $a_v \approx 1.5g$. When the target performs a manoeuvre the process noise variance is set to $1600m^2$, i.e. $a_v \approx 4g$.

Communications Process

This module provides the interface between different platforms. All information communicated to and from the platform are recorded and maintained at the communication process. This provides the platform with the ability to calculate the new information that it needs to transmit without multiple data count problems occurring at the receiver.

Here the following assumptions are made:

1. The platforms are in a fully connected topology.

2. A broadcast communication protocol is employed.
3. Communication failure occurs in complete and unambiguous mode, i.e. no receivers obtain information, and all platforms are aware of the failure.

The above assumptions ensure that only one channel filter need be maintained for each platform. Relaxation of the assumptions would result in a channel filter having to be maintained for each communication link. Further, it is assumed that each communication is synchronised with the sensor measurements and uses the associated global process noise model. These equations are provided in Section 5.4.1.

Situation and Threat Assessment Processes

These processes provide information on situation and threat assessment for the individual, sub-group and full-group of platforms. This provides the pilot (or other autonomous module) with information that may influence short term mission planning and execution. These modules are not employed, *per se*, in the simulation. However, the effect of mission planning and execution is crudely employed off-line when the trajectories of the enemy and friendly aircraft are programmed within the World Module of the simulation.

6.3.4 Communication Model Module

This module reflects the transmission characteristics of the communications links within the simulation. The probability of a communication being successful is dependent on several physical and situation related factors. These include:

1. The performance of the transmitting and receiving electronics.
2. The size of the transmitting and receiving antennas.
3. The power output of the transmitter.
4. The encoding scheme.
5. The baseband communication frequency.
6. The distance between transmitters and receivers.
7. The environmental weather conditions between transmitters and receivers.
8. The electronic noise levels between transmitters and receivers due to enemy 'jamming' techniques.

For the purposes of this thesis the effects of all these factors are combined to provide a single value for the probability of a communication. Further, this value is constant throughout the simulation and indifferent between all possible transmitter-receiver pairs. In addition it is assumed that, upon a broadcast failure, none of the receivers obtain a communication and the transmitter is aware of this. When a communication failure occurs, the transmitting node effectively misses its opportunity to communicate.

For the results presented in this thesis, the value of the probability of a communication, P_c, is set to 0.99. This may seem high, however, this value is related to the inter-platform bandwidth. Crudely, a low value of P_c can be employed with a high value of inter-platform bandwidth *or* a high value of P_c can be employed with a low value of inter-platform bandwidth. Here the latter is employed.

6.3.5 Analysis Tools

Random uncertainties in the simulator data requires that Monte-Carlo simulations are run in order to establish mean system performance. The number of Monte Carlo simulations employed is dependent on a number of factors. These include: (i) the convergence characteristics of the system, and (ii) the cost of the simulation in terms of computing time and engineering man power. These are somewhat in conflict as the convergence characteristics will be better for large Monte Carlo simulations, however, this will be costly in terms of engineering time. As a compromise the results presented in this thesis are based on 100 Monte Carlo simulations. The suitability of this value is tested during the investigations.

A range of on- and off-line statistics were computed. In particular the following quantities were obtained:

1. 90 percentile average determinant value of target track covariances.
2. 90 percentile average time to identify targets to a probability value of 0.8.

The method employed to calculate these values will be dependent on the *nature* of the data. It is envisaged that one of the methods discussed in Section 5.5.1 will be appropriate.

6.3.6 Display Tool

A Java based display tool has been set-up as a means of conveniently demonstrating some of the results obtained from the investigations. Here an OS map of Anglesey, North Wales, of area approximately 50 *km* by 30 *km* is employed as a background for the simulation.

The enemy and friendly aircraft are displayed as red and blue icons respectively. Three types of aircraft are displayed, hawk (fighter), SU27 (advanced fighter) and B52 (bomber). A '?' icon also exists to show that a target identity is unknown.

Figures 6.5 and 6.6 show the graphical output of the tool. Figure 6.5 provides a representation of the tool's 'introduction screen', while Figure 6.6 is a snapshot of a pre-programmed test scenario.

Figure 6.5: Graphics tool: Introduction and Object key.

The graphical tool can be used to display a number of different scenarios as 'canned' data generated from the demonstrator simulator.

The section has answered the question 'how has the decentralised simulator been implemented?' This has been achieved by providing details of the structure of the simulator. This includes a world module, platform module, communications module, analysis tool and display tool.

6.4 Platform and Target Scenarios

This section aims to answer the question 'how have the platforms and targets been configured for the investigations?' This question is answered below:

6.4.1 Battlespace Scenarios

The simulation is 'loosely' based on a battlespace scenario. Here two, three or four friendly aircraft intercept five probable enemy aircraft. These potentially hostile aircraft can be one of three types: bomber, fighter aircraft or advanced fighter aircraft. The friendly aircraft are equipped with sensors, e.g. electronically scanned array (ESA) radars. These view the enemy aircraft or targets to provide track and identification data that is input to

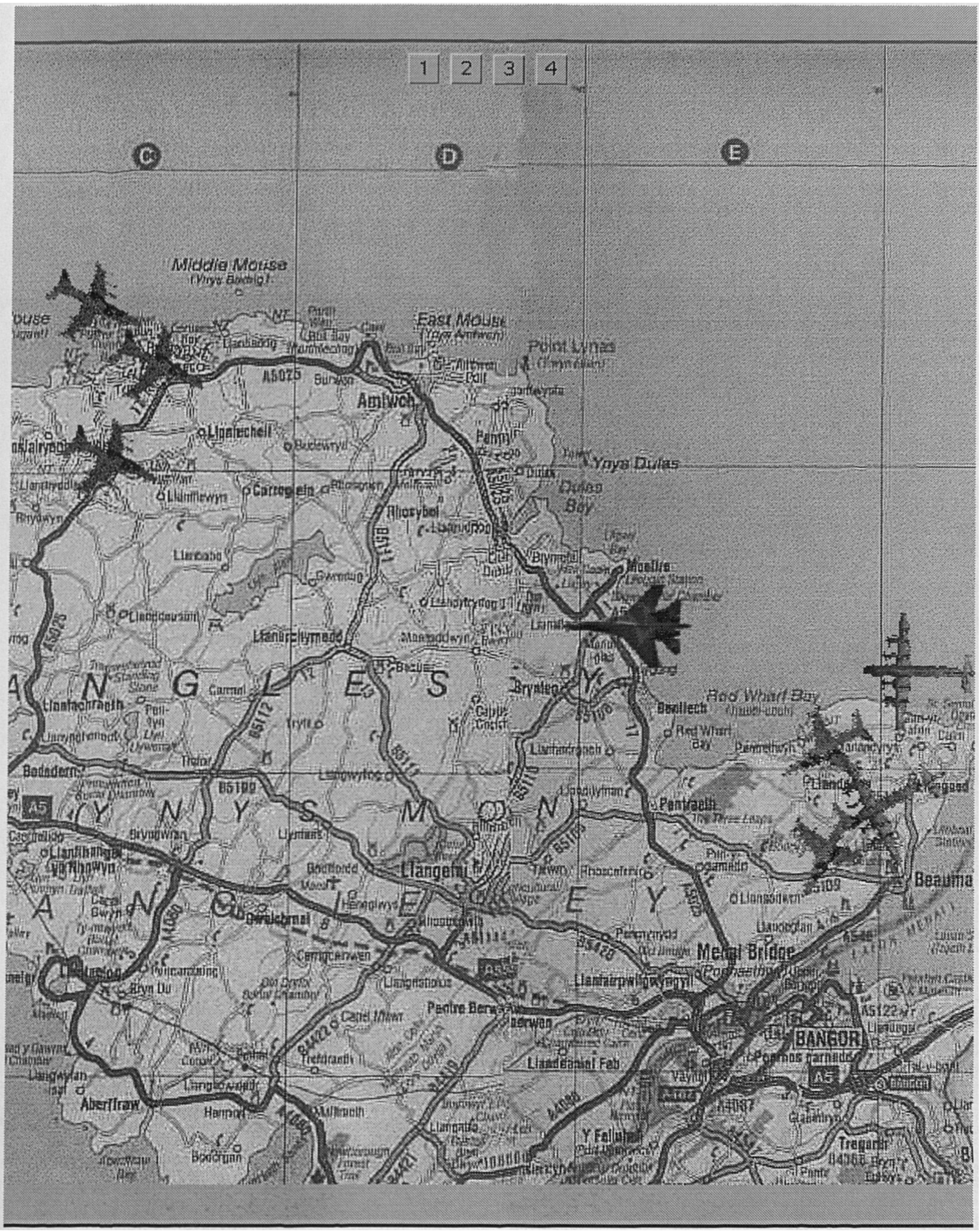


Figure 6.6: Graphics tool: Results Display.

the estimation processes. For the scenarios investigated in this thesis the friendly aircraft are of similar type and are equipped with identical sensors.

6.4.2 Scenario 1: 'Least Favourable' Targets

In this scenario (see Figure 6.7) the five most difficult to identify targets, i.e. the advanced fighters, are all performing the most difficult tracking trajectory, i.e. they are all performing manoeuvres.

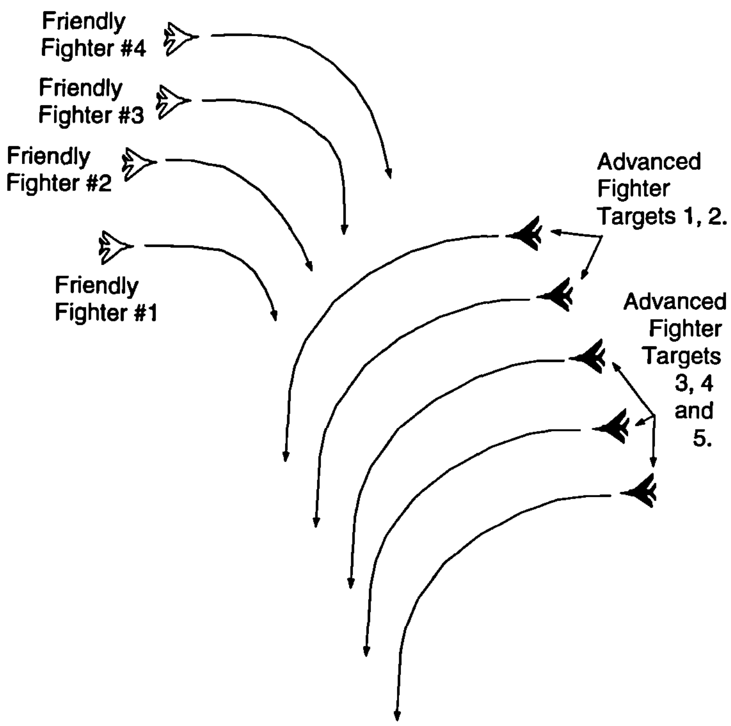


Figure 6.7: Scenario 1: 'Least favourable' targets.

6.4.3 Scenario 2: 'Most Favourable' Targets

In this scenario (see Figure 6.8) the five most easily identifiable targets, i.e. the bombers, are all performing the easiest tracking trajectory, i.e. moving with a constant velocity.

6.4.4 Scenario 3: 'Mixed' Targets

In this scenario (see Figure 6.9) the targets are of a mixed type, two bombers, two fighters and one advanced fighter. In addition, they are all performing different manoeuvres, i.e.

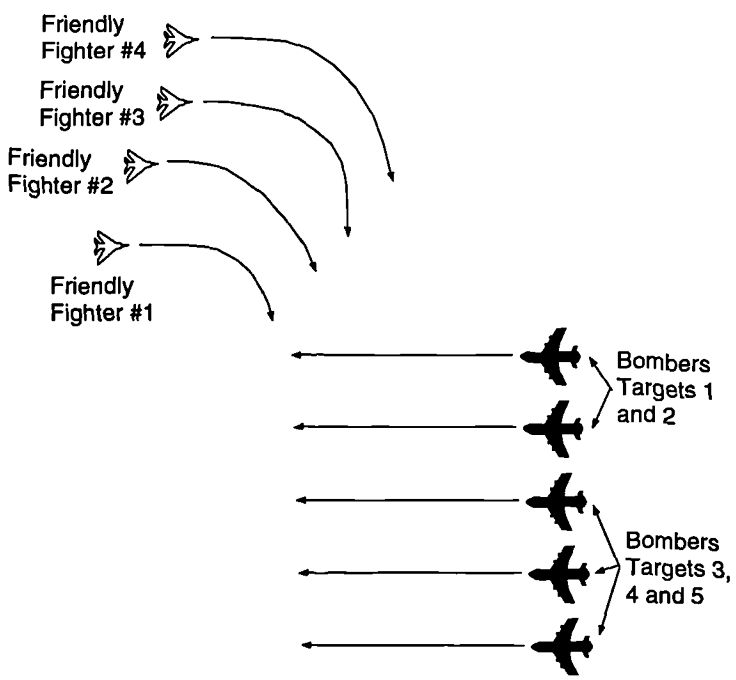


Figure 6.8: Scenario 2: 'Most favourable' targets.

four of the targets manoeuvre, but these take place at different times during the 'run'.

> The section has answered the question 'how have the platforms and targets been configured for the investigations?' This has been achieved by providing a description of the battlespace scenarios that will be employed in the thesis investigations. Further, the trajectories of the platforms and targets are represented diagrammatically.

6.5 Evaluation Test Scenarios

This section of the thesis aims to answer the question 'how will the communications management evaluation hypotheses be tested?' This is achieved as follows:

1. **Individual management, H1:** This investigation is aimed at determining the effect of employing a communications management algorithm using decision values based on the track *or* identification information metrics individually.

   Here three friendly aircraft, i.e. Fighter aircraft # 1 to # 3, intercept the 'mixed' target scenario. The friendly aircraft employ the medium performance sensor. A high performance processor is employed which ensures accurate decision values, i.e. 95% correct.

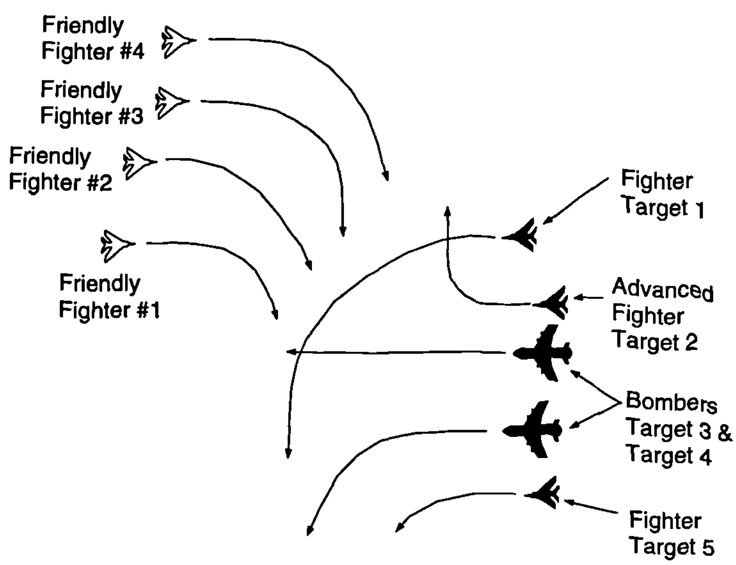


Figure 6.9: Scenario 3: Mixed targets.

2. **Combined management, H2:** This investigation is aimed at determining the effect of employing communications management decision values based on the track *and* identification information metrics in combination.

   Here three friendly aircraft, i.e. Fighter aircraft # 1 to # 3, intercept the 'mixed' target scenario. The friendly aircraft employ the medium performance sensor. A high performance processor is employed which ensures accurate decision values, i.e. 95% correct.

3. **Scenario dependance, H3:** This investigation is aimed at determining the effect of employing communications management (combined management scheme) in different target scenarios.

   Here three friendly aircraft, i.e. Fighter aircraft # 1 to # 3, intercept the 'least' favourable, 'most' favourable and 'mixed' target scenarios. The friendly aircraft employ the medium performance sensor. A high performance processor is employed which ensures accurate decision values, i.e. 95% correct.

The section has answered the question 'how will the communications management evaluation hypotheses be evaluated?' This has been achieved by providing details of the test scenarios employed for the *evaluation* hypotheses, i.e. H1, H2 and H3.

6.6 Application Test Scenarios

This section of the thesis aims to answer the question 'how will the communications management application hypotheses be tested?' This is achieved as follows:

1. **Processor trade-off, H4:** This investigation is aimed at determining the effect of employing processors of different performance characteristics to compute the communications management algorithm. This manifests itself as a reduction in the accuracy of the decision values employed in determining the most appropriate data to communicate. This is done by introducing random noise to the decision values.

   The intelligent communications management algorithm predicts the benefit, to the total system, of transmitting each target in turn. This results in a list of scalar information values, one for each target in the system. This is represented in Figure 6.10(a). Here the benefit is plotted for each target (5 in this case). Therefore in order to maximise the information benefit to the system the preferred target communication order is 3, 2, 4, 1 and 5.

   These decision values will be prone to systematic and random variations. Here we consider the effect that random noise has on the decision values. The method employed in introducing noise to the decision values is now presented:

   (a) Calculate the reduction for each individual decision value from the percentage noise, $n_t\%$[2]. This value is set-up prior to running the simulation. The following calculation provides the reduction value, r:

   $$r = \frac{n_t\%}{N \times 100} \sum_{\forall i \in \{1 \ldots N\}} d_i \tag{6.2}$$

   where N is the number of targets.

   (b) The decision values are then all reduced by the value r, i.e.

   $$\forall i \in \{1 \ldots N\} \qquad d_i = d_i - r \tag{6.3}$$

   This is represented in Figure 6.10(b). It should be noted that if $d_i - r$ is negative then this *surplus* is divided equally amongst the other targets. The decision value for that particular target is then set to zero.

   (c) A random value, p_i, in the range 0 to $N \times r$, taken from a 'flat' distribution, is than added to each target decision value, i.e.

   $$\forall i \in \{1 \ldots N\} \qquad d_i = d_i + p_i. \tag{6.4}$$

[2]The decision noise percentage is 100 - the decision accuracy.

subject to the constraint that,

$$\sum_{\forall i \in \{1 \dots N\}} p_i \equiv N \times r \tag{6.5}$$

This is represented in Figure 6.10(c).

Note that in the example shown in Figure 6.10, the communication order has changed to 2, 3, 4, 5, and 1. For this processor performance representation a decision accuracy of 100% ensures that the *correct* target data is transmitted at each communications. When the decision accuracy is 0% the target data for communications is selected randomly from a *flat* distribution.

In this scenario, the three friendly aircraft, i.e. Fighter aircraft # 1 to # 3, intercept the 'mixed' target configuration. The friendly aircraft employ the medium performance sensor. Here the performance of the processor is varied by changing the accuracy of the decision values to 0, 25, 50, 75, 95 and 100 % .

2. **Sensor trade-off, H5:** This investigation is aimed at determining the effect on system performance of employing sensors of different characteristics.

   Here three friendly aircraft, i.e. Fighter aircraft # 1 to # 3, intercept the 'mixed' target configuration. The friendly aircraft employ the high performance processor that allows the decision values to be determined to an accuracy of 95%. The sensor is varied from low, medium to high performance.

3. **Number of platforms trade-off, H6:** This investigation is aimed at determining the effect of employing different number of platforms on the system performance.

   Here an intercept mission is analysed for the 'mixed' target configuration. The friendly aircraft employ the high performance processor that allows the decision values to be determined to an accuracy of 95%. The sensor employed is of medium performance characteristics. The number of platforms employed is varied between 2, 3 and 4.

4. **Multi-resource trade-off, H7:** This investigation is aimed at demonstrating that the results obtained can be applied to the engineering problem of system design. Here the results of using different processors (low, medium or high performance), different sensors (low, medium or high performance), different number of platforms (2, 3 or 4) and different inter-platform communications bandwidths (0, 60 100 %) will be stored in a database. This provides a maximum of 81, i.e,. 3^4, different configurations. A subset of these may be used to achieve the customers technical specification of tracking and identification performance.

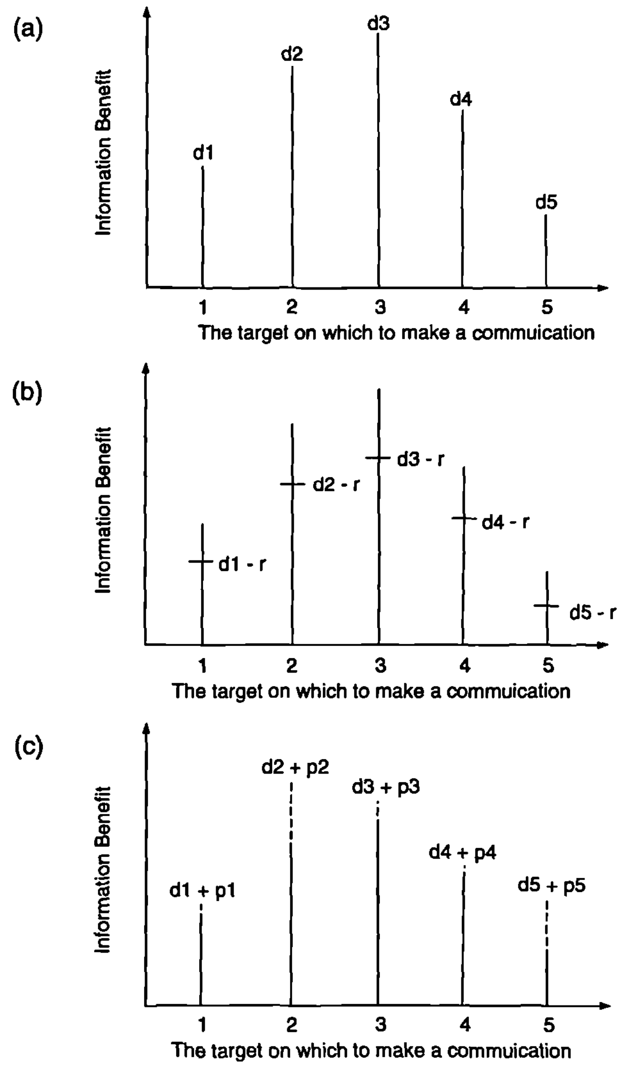


Figure 6.10: Introducing noise to the decision values.

The final selection will be made on some criteria such as financial cost. Each processor, sensor, platform numbers, and communication system will incur an associated cost in £. If the selection is based on minimising this cost, then the system with the least cost, from the subset of configurations that achieve the technical specification will be selected.

The section has answered the question 'how will the communications management application hypotheses be tested?' This has been achieved by providing details of the test scenarios employed for the *application* hypotheses, i.e. H4, H5, H6 and H7.

6.7 System Performance Metrics

This section aims to answer the question 'how will the system performance be measured?' This is achieved by considering the raw profiles, quantitative metrics, distribution profiles, Monte Carlo numbers and process model development.

6.7.1 Raw Profiles

Figure 6.11 (a) and (b) provide a single run example of the track and identification data respectively. These were obtained at a single platform for a mixed scenario employing an inter-communications bandwidth of 20%, i.e. communicating on only one target per communication time slot. Here the y axis provides a measure of the uncertainty 'volume' associated with a targets position, for the track plot, and a measure of the maximum probability from the identification estimate vector on the identification plot. The x axis provides the time since the start of the simulation in seconds. The performance against each target is overlaid on the appropriate plot. Figure 6.12 (a) and (b) provide corresponding plots for a similar simulation with an inter-nodal communications frequency of 80%.

Deciding which of the 'raw' results provides the better performance can be carried-out by eye. The determinant of the track covariance in Figure 6.11 (a) is greater than that in Figure 6.12 (a). Further, the identification times for Figure 6.11 (b) converge slower than those presented in Figure 6.12 (b). However, such a *qualitative* method can become difficult if results obtained are not so 'clear-cut' or if several platforms have to be considered. This problem can be overcome by employing *quantitative* measures which aim to summarise statistically the system performance. A common metric employed for such applications is based on *averaging*. However, before defining such a metric, further analysis of the processes contributing to the track and identification profiles is required.

Some of the track determinants exhibit large leaps in values at certain times. These occur when the targets perform a manoeuvre and are due to the tracking algorithm employing a larger process noise value. Further, the effect of the TDMA communication protocol, along with incomplete communications and missed observations, add further 'glitches' to the profile. The identification profile exhibits step increases which occur when a communication is received from another platform. Again, the profile of the identification plot is affected by the communication protocol, incomplete communications and missed observations. Therefore, the profiles of the track and identification plots are dependent on systematic variations due to the communication protocol[3] and random variations due to in-perfect communications systems and sensors. Hence, in order to summarise the effect of the random component on the results obtained a number of *Monte Carlo* simulations have to be carried out.

In summary, the qualitative result that can be obtained by comparing the track and identification plots for simulations employing different system characteristics, e.g. inter-nodal communications bandwidth, can be enhanced by quantitative metrics which statistically summarise system performance, i.e. averaging metrics. Further, in order to summarise the effect of random components Monte Carlo simulations will be employed.

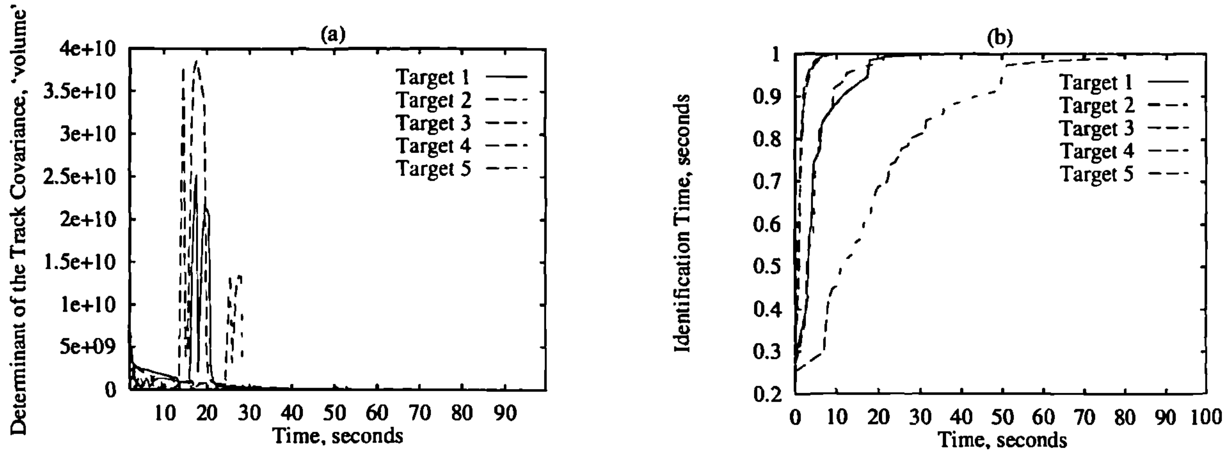
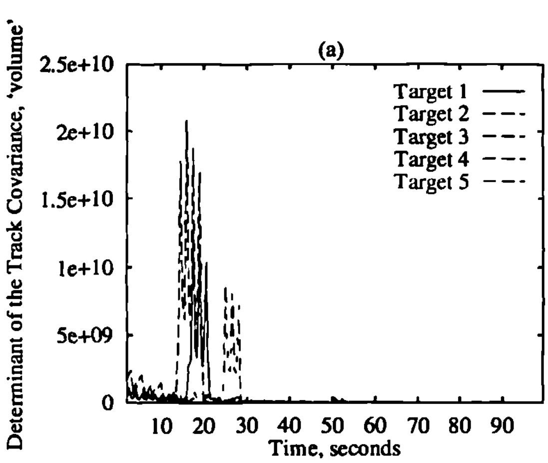


Figure 6.11: (a) track and (b) identification results for a single run 'mixed' scenario with an inter-nodal communications bandwidth of 20%.

[3]It should be noted that this also has a random component related to the order in which the friendly aircraft communicate.



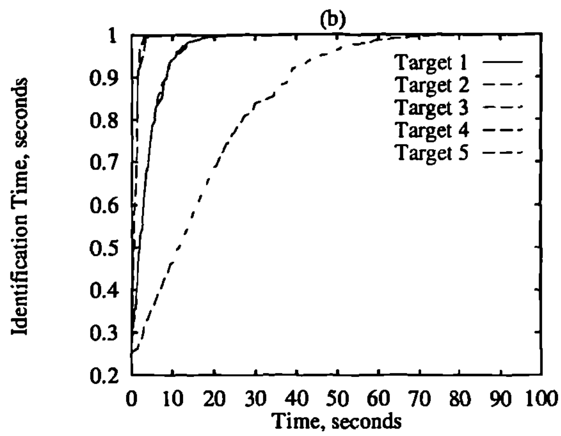


Figure 6.12: (a) track and (b) identification results for a single run 'mixed' scenario with an inter-nodal communications bandwidth of 80%.

6.7.2 Quantitative Metrics

In this section quantitative metrics are defined for system level performance evaluation of the simulation results. More complex measures of effectiveness (MOEs) are described in (Blackman 1986). These combine tracking performance with other issues such as data association that are then normalised. The approach employed here follows that provided in (Alford et al. 1996). This is based on the analysis of the track covariance. For the work presented in this document only the determinant of the covariance is considered as it combines the distance and velocity uncertainties for all the dimensions into a single (volume) value. The identification performance metric is based on the time take to identify the target to a given identity probability.

This tracking performance metric is defined as[4]:

$$|\mathbf{P}|_{\text{ave}} = \frac{1}{K \times N \times T} \sum_{\forall k \in K} \sum_{\forall i \in N} \sum_{\forall t \in T} |{}^t\mathbf{P}_i(k|k)| \tag{6.6}$$

where k is the time index, i is the node index and t is the target index. The identification metric is defined as:

$$\tau_{\text{ave}} = \frac{1}{N \times T} \sum_{\forall i \in N} \sum_{\forall t \in T} {}^t\tau_i \tag{6.7}$$

where τ is the time to reach a probability level of 0.8,

[4]It should be noted that k=0 is excluded from the results since the determinant of the covariance would be ∞

6.7.3 Distribution Profiles

In this section the distribution profiles for the system performance metrics over a number of Monte Carlo simulations are considered. Results are presented for all three scenarios, i.e. most favourable, mixed and least favourable, employing an inter-platform communications bandwidth of 80%, high performance processors, medium performance sensors and three platforms.

The track and identification profiles are represented in Figures 6.13 (a) and (b) respectively. These were obtained by carrying out 100 Monte Carlo simulations. The y axis provides the percentage frequency of occurrence. The x axis provides the average determinant of the track covariance, i.e. $|\mathbf{P}|_{\text{ave}}$, in (a) and average identification time , i.e. τ_{ave}, in (b). It should be noted that different bin sizes have been used for each plot. This ensures that the resolution of the contour is not lost.

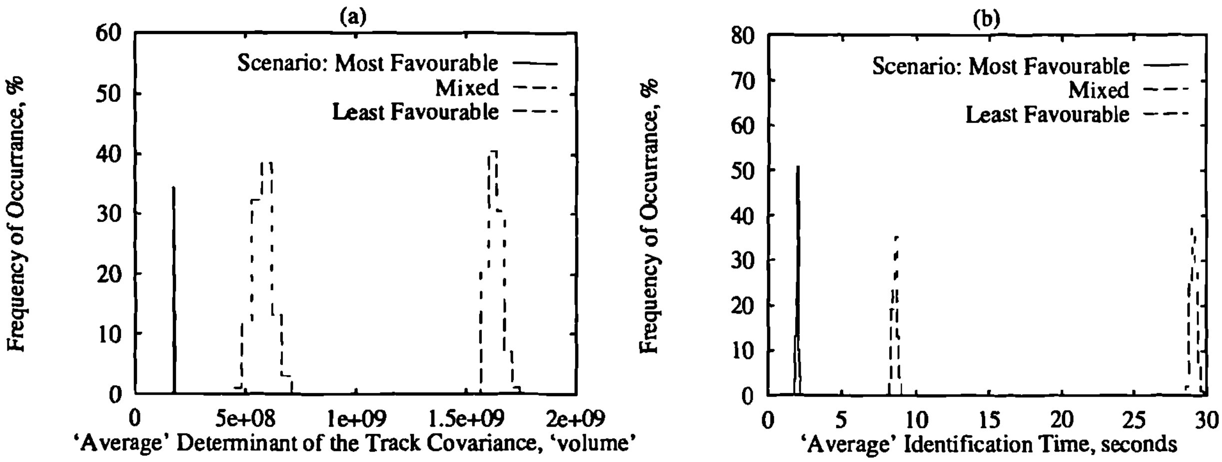


Figure 6.13: (a) track and (b) identification profiles for the scenarios investigated.

6.7.4 The Monte Carlo Number

An important issue for Monte Carlo simulations is whether enough runs have been carried-out. In this section we determine if 100 runs is suitable.

This is determined by carrying out multiple runs of the same scenario (with a different random seeds). The error on the 90th percentile measurement can then be determined. This investigation was carried out on the mixed target scenario, where three platforms employed the medium performance sensor with high performance processors (95% accurate decision values) operating at an inter-platform communications management of 40%

Values	Information based		Round Robin	
	Track	Identification	Track	Identification
standard deviation of the sample, s.	0.23%	0.00%	6.10%	0.70%
standard error in a single simulation, σ_s.	0.09%	0.00%	2.30%	0.26%

Table 6.1: Standard errors in the simulation, where $\sigma_s = \frac{s}{\sqrt{n}}$ and n - is the number in the sample.

full bandwidth. Results were gathered for the information theoretic algorithm and the round robin algorithm. These are tabulated in Table 6.1 with the standard error in the simulation.

It should be noted that the errors for both communications management algorithms are relatively small (especially for the information based algorithm). Further, the errors at 0% and 100% full bandwidth should reduce to zero. This situation arises since either non or all target data is communicated respectively.

Completing multiple runs of the 100 Monte Carlo simulations is very computationally expensive. In addition, these runs take a considerable time to complete, i.e. the order of days. As such standard errors for each simulation scenario are not carried out. However, the values provided in Table 6.1 will be used as representative maximum errors.

6.7.5 Process Model Development

This section provides details of how the process models of the thesis were developed.

Not all the Monte Carlo profiles in Figures 6.13((a) and (b)) are Gaussian in shape. Hence, the counting method, as described in Section 5.5.1, will be employed to develop the process models of the thesis. The remainder of the process models presented in this chapter have the percentage of inter-platform bandwidth plotted on the x axis with the track and identification performance metric plotted on the y axis, see the examples in Figure 6.14 (a) and (b) respectively. These indicate that 90% of the results were obtained from the simulation lie below the plots and 10% above, i.e. the 90th percentile.

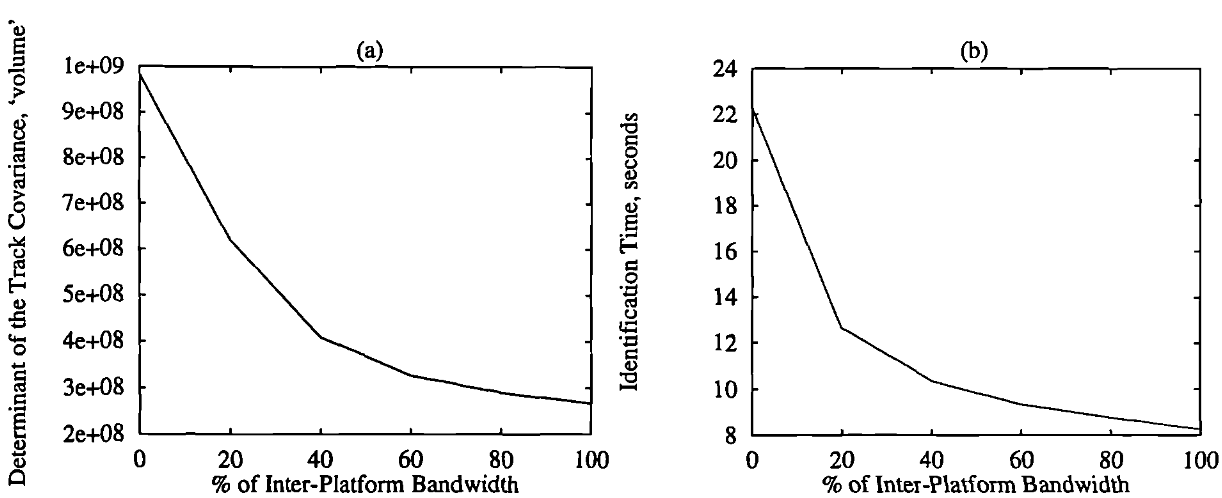


Figure 6.14: Example track (a) and identification (b) process models.

The section has answered the question 'how will the system performance be measured?' The analysis of system performance metrics has provided a means of statistically representing track and identification performance from a number of targets, from a number of platforms, over a number of Monte Carlo simulations. Further, the results indicate, that for the scenarios investigated, 100 Monte Carlo simulations is adequate. The system performance metrics can be applied to developing process models that relate the track and identification performance to a limited communications bandwidth resource that is managed.

6.8 Summary and Concluding Remarks

This chapter of the dissertation has answered the question 'how will the communications management evaluation and application hypotheses be tested?' This has been achieved through the sections of the chapter.

The Evaluation Test Scenarios will be applied in Chapter 7: An Evaluation of Communications Management, and the Application Test Scenarios will be used in Chapter 8: Towards Decentralised System Design.

Chapter 7

An Evaluation of Communications Management

7.1 Introduction

This chapter provides the results, analysis and discussion of the investigations into the evaluation of decentralised communications management. The aim here is to test the evaluation hypotheses H1, H2 and H3. This process lends support to the thesis evaluation proposition, i.e. Proposition 1.

The connectivity between different sections of this chapter are provided in Figure 7.1. Sections 7.2, 7.3 and 7.4 provide the results, analysis and discussions associated with comparing the performance of an information theoretic approach to communications management with that of a round robin method. In Section 7.2 the comparison is made when the information theoretic algorithm is based on track or identification data considered individually, i.e. *individual management.* This investigation is developed in Section 7.3 by comparing the round robin method with an information theoretic algorithm based on a combination of track and identification data, i.e. *combined management.* Section 7.4 compares the algorithms performance for different target scenarios. A summary and conclusions of the work are provided in Section 7.5.

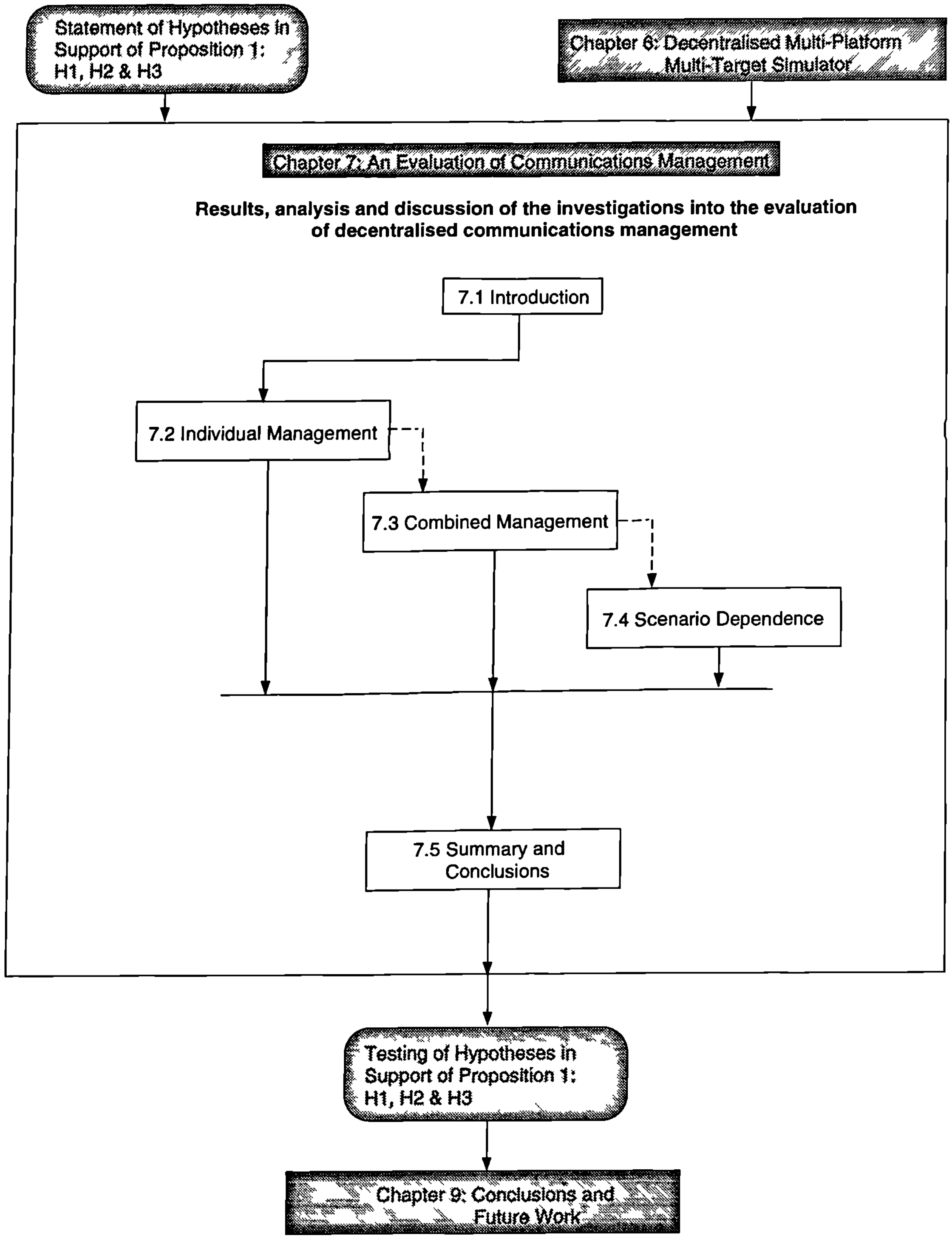


Figure 7.1: Reader's map for Chapter 7.

7.2 Individual Management

Here a comparison is made between the track and identification performance of an information theoretic approach to communications management based on track *or* identification data considered individually with a round robin algorithm.

7.2.1 Investigation Results

The results generated from the simulation investigation detailed in Section 6.5 are provided in the process models of Figures 7.2 and 7.3. Figure 7.2 provides the results generated when the information theoretic algorithm was based on the track data. In Figure 7.3 the results generated when the information theoretic algorithm was based on identification data are represented. In each case (a) depicts the system tracking performance and (b) the identification performance.

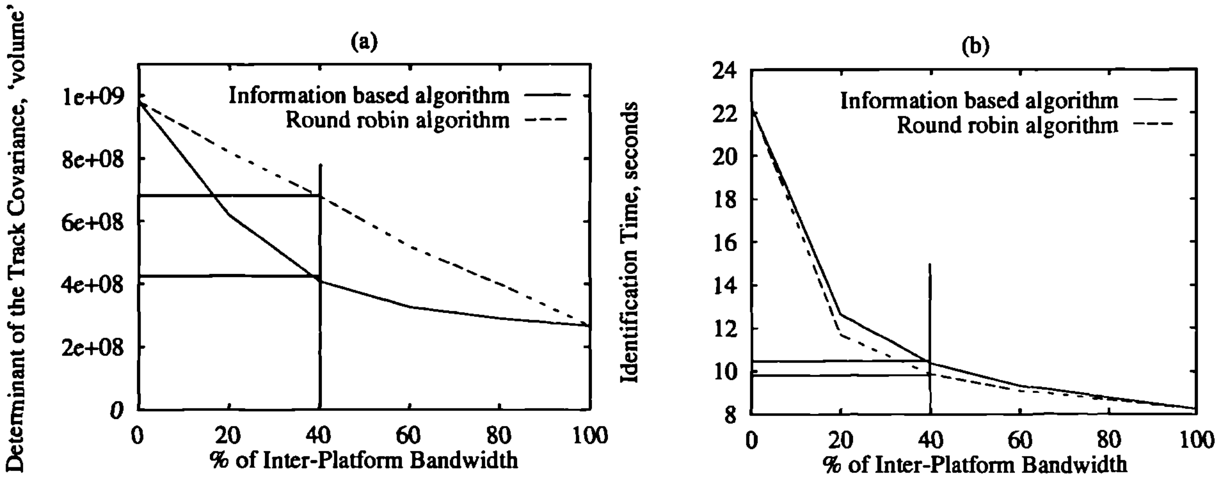


Figure 7.2: Track only based communications management: (a) tracking and (b) identification performance.

7.2.2 Analysis and Discussion

The track performance for the round robin approach is approximately linear in its behaviour for the range of communications bandwidth considered. Further, forb the identification performance of the round robin algorithm, a large decrease in average identification time is experienced due to the introduction of a small communications bandwidth, i.e. a reduction of approximately 10s is observed when zero bandwidth is incremented to 20%

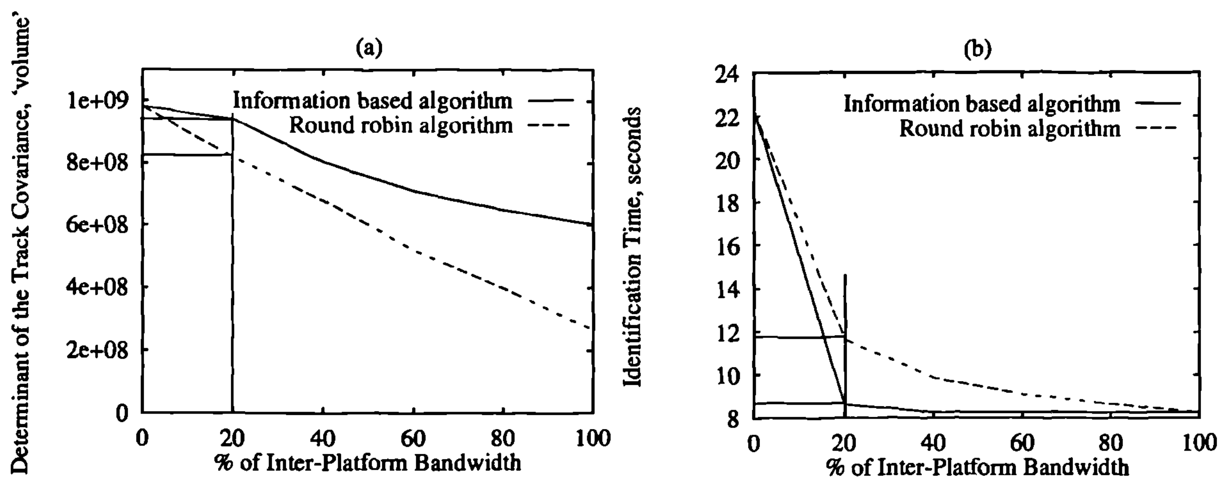


Figure 7.3: Identification only based information management: (a) tracking and (b) identification performance.

full bandwidth. Further increase in the inter-platform communications bandwidth only reduces the identification time by approximately 3s for an increase of 20% to 100% in bandwidth. This situation arises since the track information degrades temporally whereas the identification information does not.

The results provide good evidence that applying an information theoretic approach to communications management based on track data provides improved track performance when compared with the round robin algorithm. For example, consider the performance of the algorithms in Figure 7.2 (a) at an inter-platform communications bandwidth of 40%. Here the information based algorithm has an average track uncertainty of approximately 4.2e8, whereas the round robin approach has a performance of approximately 6.9e8, i.e. an increase of $\approx$ 64% or $\approx 28\sigma_s$ of the round robin standard errors (see Table 6.1).

Similarly, improved identification performance is experienced for the identification only based information theoretic approach when compared with the round robin algorithm at a communications bandwidth of 20%. For example, in Figure 7.3 (b) the information based algorithm has an identification time of 8.9s whereas the round robin has an average identification time of 11.7s, i.e. an increase of $\approx$ 31% or $\approx 119\sigma_s$ of the round robin standard errors.

These examples provide experimental simulation evidence that supports the *rejection* of the hypothesis, H1, i.e.

> **Evaluation Hypothesis H1:** Individual management.
> 'An information theoretic approach to communications management, based on track or identification information, never provides a measurable increase in performance when compared with a round-robin approach.'
> **Status: REJECTED** (Deaves et al. 1997a, Deaves et al. 1997b) with high confidence.

It should be noted that when the track only information theoretic approach is employed the identification performance of the round robin technique is better than that of the information based algorithm. For example, in Figure 7.2 (b) at an inter-platform communications bandwidth of 40% the round robin approach has an average identification time that is less than $10s$ whereas the information based algorithm has a performance which is greater than $10s$.

Similarly, when an identification only information theoretic approach is employed the track performance of the round robin technique out-performs the information based algorithm. An example of this is provided in Figure 7.3 (a). Here at 20% of the full inter-platform communications bandwidth the track performance of the round robin algorithm is approximately 8.2e8 whereas the information based algorithm has a performance of approximately 9.5e8.

So we observe that an information theoretic approach based on track information is able to improve tracking performance but does not (necessarily) improve the identification performance, and vice versa.

In order to overcome these drawbacks with the information based algorithm a decision metric based on the combination of track and identification information will be considered.

7.3 Combined Management

This section compares the performance of track *and* identification based information theoretic algorithm, i.e. combined management, with a round robin approach to communications management.

7.3.1 Investigation Results

The simulation investigation detailed in Section 6.5 generates the process models of Figure 7.4. The system tracking performance is represented in (a) while the identification results are represented in (b).

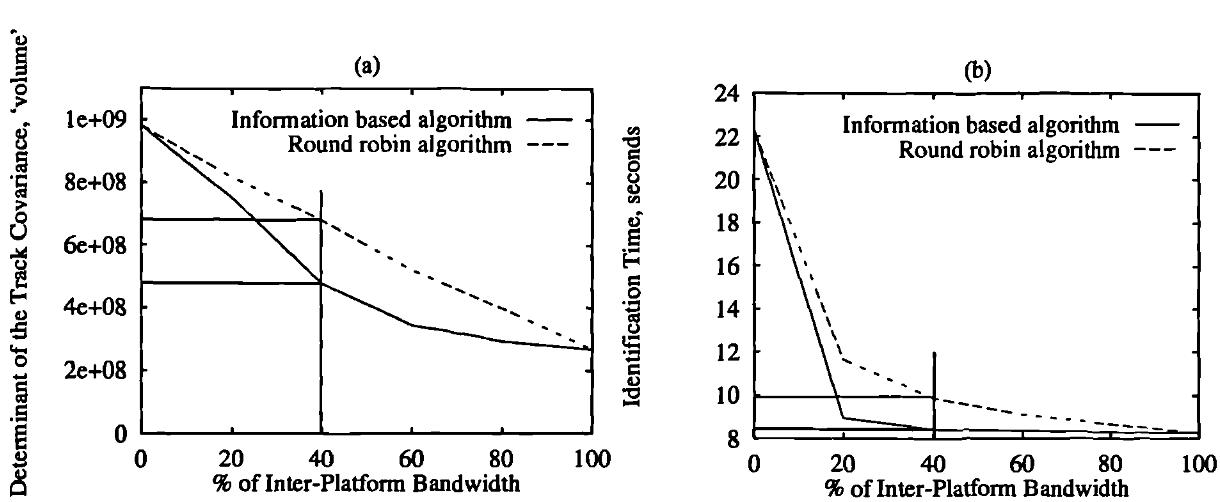


Figure 7.4: Combined philosophy communications management: (a) tracking and (b) identification performance.

7.3.2 Analysis and Discussion

The results indicate that the combined management philosophy provides the information theoretic approach with improved track and identification performance simultaneously when compared with the round robin approach. For example, at an inter-platform communications bandwidth of 40% the performance of the information based algorithm is approximately $4.8e8$ and $8.5s$ for track and identification respectively. The corresponding performance for the round robin approach is approximately $6.8e8$ and $10s$. Therefore, the round robin algorithm introduces percentage increases of $\approx$ 42% ($\approx 18\sigma_s$ of the round robin standard errors) and $\approx$ 14% ($\approx 54\sigma_s$ of the round robin standard errors) for the track and identification performance metrics respectively.

This example provides experimental simulation evidence that supports the *rejection* of the hypothesis, H2, i.e.

Evaluation Hypothesis H2: Combined management.
'A combined decision metric, based on track and identification information, never provides a measurable increase in performance when compared with a round-robin approach.'
Status: REJECTED (Deaves et al. 1998) with high confidence.

Figure 7.5 compares the performance of the combined management philosophy with the individual management approach. In Figure 7.5 (a) the track performance of the track only based management algorithm are compared with the combined management results.

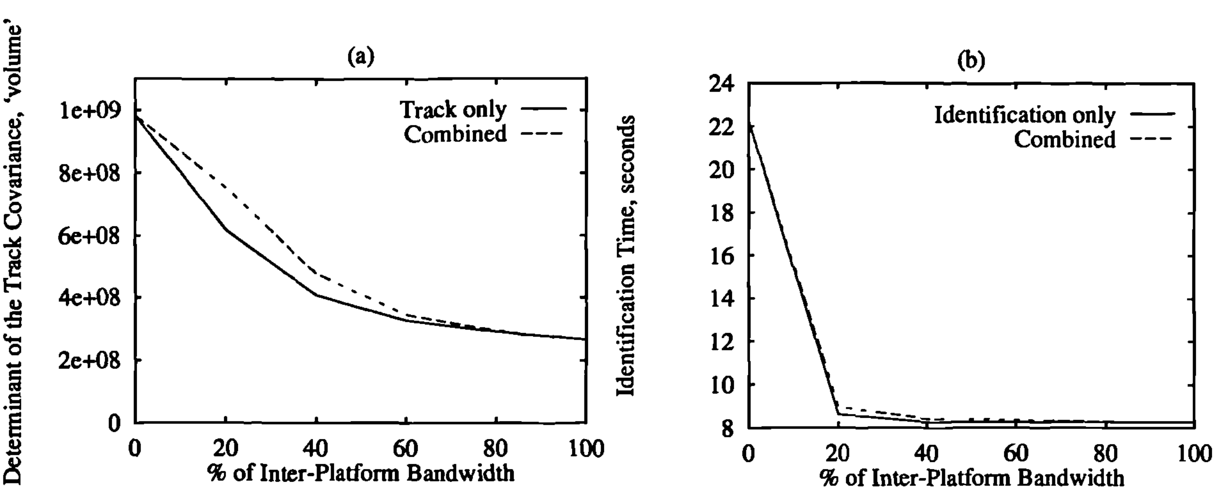


Figure 7.5: Comparison of the track and identification only philosophy with combined management: (a) tracking and (b) identification performance.

This indicates, as might be expected, that the individual management philosophy outperforms the combined management approach. Figure 7.5 (b) represents a comparison of the identification performance of the identity only based management algorithm and the combined management approach. This indicates that the identification based algorithm seems to out-perform the combined management algorithm.

7.4 Scenario Dependence

This section investigates whether there is a measurable performance difference between the combined management algorithm and round robin approach when all the targets are of the same characteristics.

7.4.1 Investigation Results

The simulation investigation detailed in Section 6.5 generates the process models of Figures 7.6 and 7.7 for the 'most favourable' and 'least favourable' scenarios respectively. Here tracking performance is represented in (a) with the identification results represented in (b).

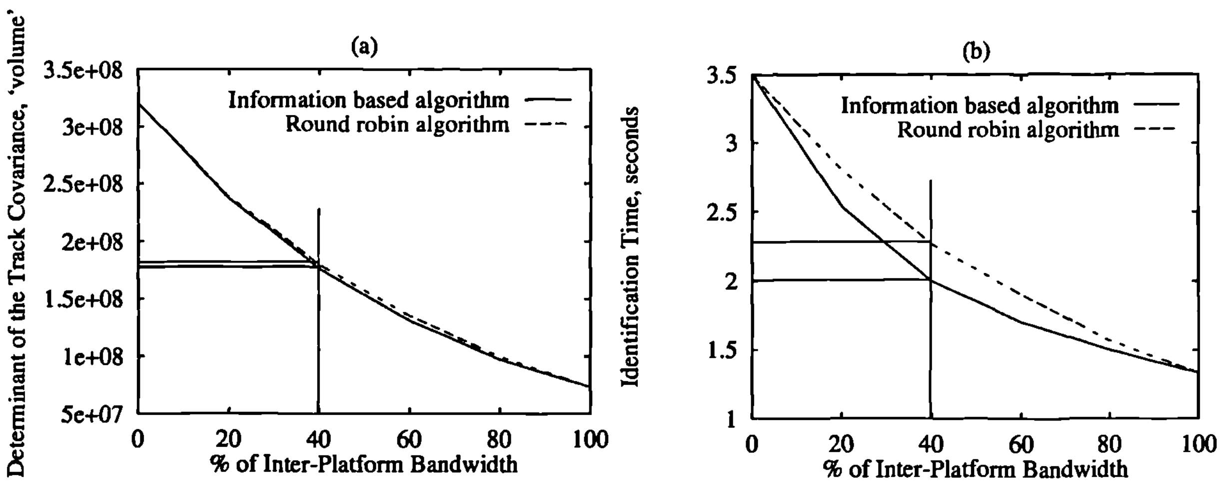


Figure 7.6: Communications management performance for the 'most favourable' scenario: (a) tracking and (b) identification.

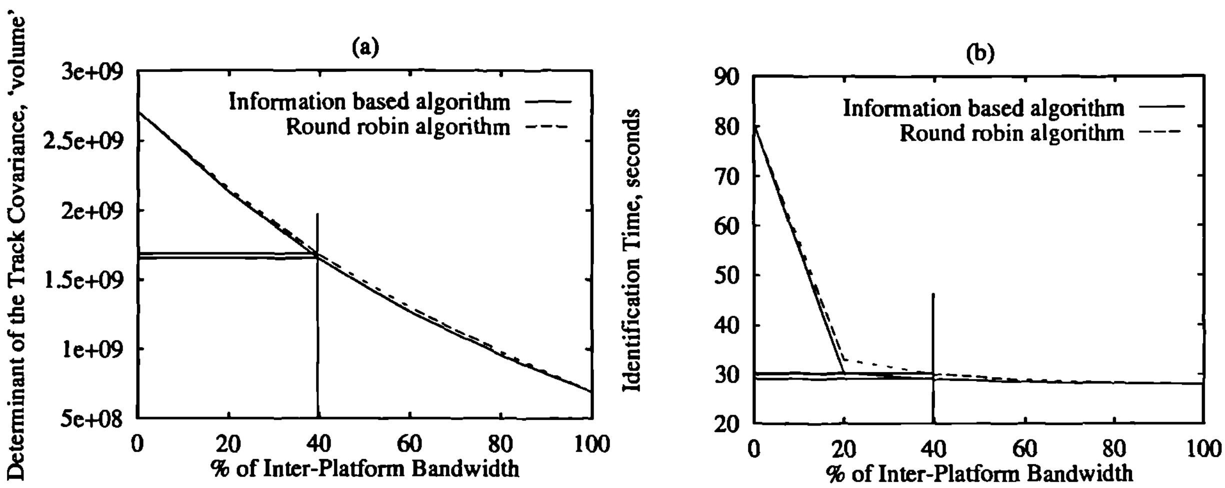


Figure 7.7: Communications management performance for the 'least favourable' scenario: (a) tracking and (b) identification.

7.4.2 Analysis and Discussion

The results of the investigation indicate that even when the scenario comprises targets that all have similar characteristics the combined information metric for communications management again provides a measurable benefit.

The results for the 'most favourable' scenario are represented in Figure 7.6. At an inter-platform communications bandwidth of 40% of the full requirement the information based algorithm gives performance values of $1.7e8$ and $2s$ for track and identification respectively. Corresponding values for the round robin algorithm are $1.8e8$ and $2.3s$. These give percentage increases of $\approx 6\%$ ($\approx 2.6\sigma_s$ of the round robin standard errors) and 15% ($\approx 58\sigma_s$ of the round robin standard errors) for track and identification respectively when employing the round robin algorithm.

The results for the 'least favourable' scenario are represented in Figure 7.7. At an inter-platform communications bandwidth of 40% the full requirement the information based algorithm gives performance values of $1.7e9$ and $28s$ for track and identification respectively. Corresponding values for the round robin algorithm are $1.75e9$ and $30s$. These give percentage increases of $\approx 3\%$ ($\approx 1.3\sigma_s$ of the round robin standard errors) and $\approx 10\%$ ($\approx 38\sigma_s$ of the round robin standard errors) for track and identification respectively when employing the round robin algorithm.

These examples provide experimental simulation evidence that supports the *rejection* of the hypothesis, H3, i.e.

> **Evaluation Hypothesis H3:** Scenario dependence.
> 'A combined decision metric, based on track and identification information, does not provide a measurable benefit, even for scenarios where the targets have different track and identification characteristics.'
> **Status: REJECTED** with a lower confidence.

It should be noted that although a performance increase can be measured for situations where the targets are of similar characteristics the percentage benefit is less than for a mixed target scenario.

7.5 Summary and Conclusions

The aim of this chapter was to *test* the thesis evaluation hypotheses H1, H2 and H3 so as to lend support to the proposition:

> **Proposition 1:** Evaluation of Communications Management.
> 'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides a measurable increase in performance when compared with ad-hoc approaches.'
> **Status: MAINTAINED**

This aim has been achieved through the thesis investigations. The results and analysis of these investigations provide empirical evidence that all three *evaluation* hypotheses can, plausibly, be rejected. Further, a number of interesting observations have been noted. These include:

1. **Individual management:** The *best* system tracking performance is obtained when the communications management is based purely on tracking. However, such a management scheme gives *poor* identification performance. A similar situation arises when the communications management is based on identification, in that the *best* identification performance will be achieved with *poor* track performance.

2. **Combined management:** A combined management approach provides *good* track and identification performance.

3. **Scenario dependence:** An information theoretic approach to communications management provides the *greatest* benefit when the information presented to the platforms is diverse.

> These points lead to the following **'rules of thumb'**:
>
> 'An information theoretic approach to communications management provides system benefit when'
>
> 1. *a combined* management algorithm is employed.
> 2. *targets of different characteristics* are being sensed.

Chapter 8

Towards The Design of Decentralised Systems

8.1 Introduction

This chapter provides the results, analysis and discussion of the investigations into the application of decentralised communications management. The aim here is to test the application hypotheses H4, H5, H6 and H7. This process lends support to the thesis application proposition, i.e. Proposition 2. In addition, the trade-off issues investigated provide an in-sight as to how process models can be applied to decentralised avionic sensing system design.

The connectivity between different sections of this chapter are provided in Figure 8.1. Sections 8.2, 8.3 and 8.4 provide the results, analysis and discussion of the knowledge gained from investigating the trade-off potential between the processor, sensor and number of platforms (respectively) employed in a decentralised avionic sensing system. These individual investigations are combined in Section 8.5 to investigate the potential for multi-resource trade-offs. A summary and conclusions of the work documented in this chapter are provided in Section 8.6.

8.2 Processor Trade-off

Here the trade-off potential between the processor performance and managed communications bandwidth employed in a decentralised avionic sensing system is investigated.

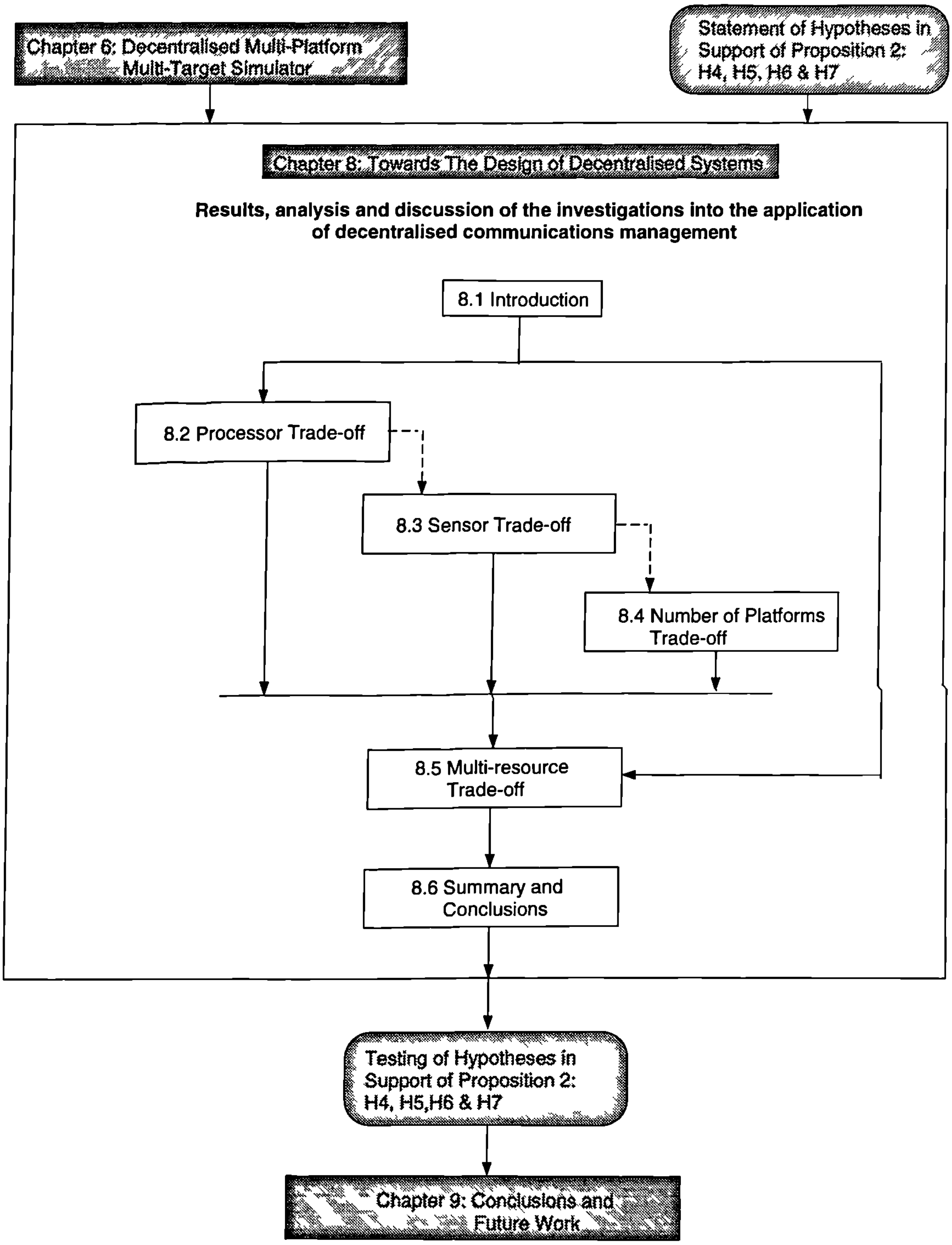


Figure 8.1: Reader's map for Chapter 8.

8.2.1 Investigation Results

The results generated from the simulation investigation detailed in Section 6.6 are provided in the process models of Figure 8.2. Here (a) and (b) represent the system tracking and identification performance respectively.

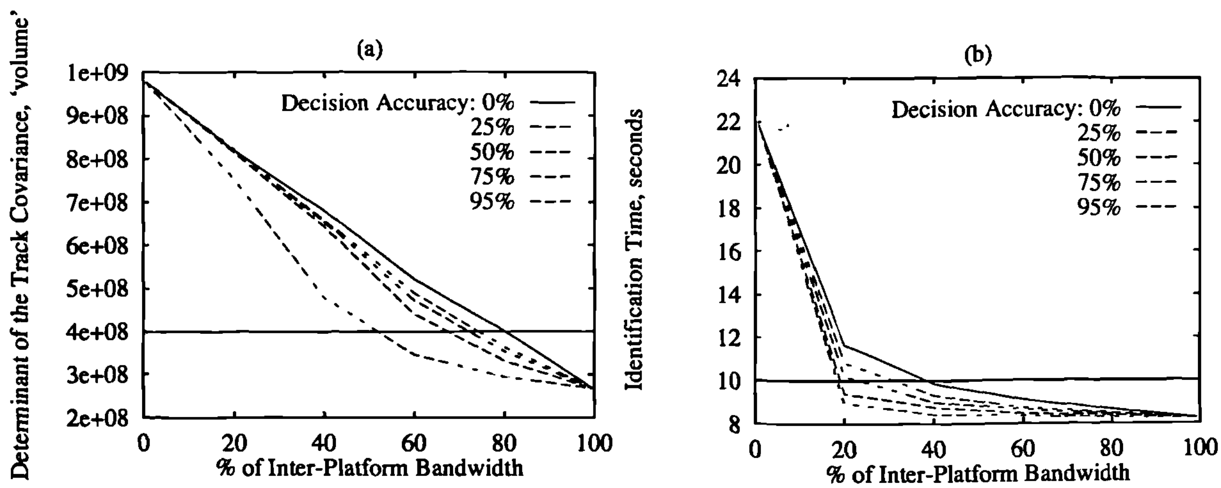


Figure 8.2: Processor and communications system trade-off potential: (a) tracking and (b) identification performance.

8.2.2 Analysis and Discussion

The results indicate that as the processor performance is increased, which results in the accuracy of the decision values being increased, the tracking and identification performance also increase.

The limits on these track and identification performance plots are provided by the 100% and 0% accurate decision values. The 100% accurate decision values ensures that a platform communicates data on the target that will maximise the posterior entropic information gain of the system on *each* communication. For the 0% accurate decision values the target data to be communicated is chosen at random[1]. It should be noted that the performance of the 100% and 0% accurate algorithms are the same at zero and full inter-platform bandwidth. This is expected since at these bandwidth either no data or all data are communicated respectively. Hence the processing performance of the communications management processor has no effect.

[1]It should be noted that a decision accuracy of 0% provides results that are very similar to those obtained from the round robin approach.

Now the trade-off potential between the processor and communication system is considered. Beginning with the system tracking performance. Consider a customer requiring an avionic sensing system with a tracking performance represented by an average covariance of $4e8$ for the scenario described in Section 6.4.4. This requirement is represented on Figure 8.2 (a) by the horizontal line $y = 4e8$. Therefore, a number of trade-off potentials exist for the customers design. For example, a system employing a processor that can achieve 95% accurate decision values (with a large margin of $> 150\sigma_s$ information based algorithm standard errors, see Table 6.1) meets the specification at 60% of the full inter-platform communications bandwidth, or a processor that can achieve 25% accurate decision values (with a margin of $3\sigma_s$ round robin standard errors) meets the specification at 80% of the full inter-platform communications bandwidth. Therefore, a trade-off exists between a high performance processor coupled with a low performance communication system *or* a low performance processor and a high performance communications system.

We now consider the system identification performance. Consider a customer requiring an avionic sensing system with an identification performance represented by an average identity time of $10s$ for the scenario described in Section 6.4.4. This requirement is represented on Figure 8.2 (b) by the horizontal line $y = 10s$. Therefore, a number of trade-off potentials exist for the customers design. For example, a system employing a processor that can achieve 75% accurate decision values meets the specification at 20% of the full inter-platform communications bandwidth, or a processor that can achieve 25% accurate decision values meets the specification at 40% of the full inter-platform communications bandwidth. These are both achieved with a margin of $\approx 30\sigma_s$ round robin standard errors. Therefore, a trade-off exists between a high performance processor coupled with a low performance communication system *or* a low performance processor and a high performance communications system.

The trade-off potentials investigated provide experimental simulation evidence that supports the *rejection* of the hypothesis, H4, i.e.

Application Hypothesis H4: Processor trade-off.
'An information theoretic approach to communications management never provides the potential for trade-off between the communication system and processor.'
Status: REJECTED (Deaves et al. 1997c) with high confidence.

It should be noted that there may be a *limit* to the prediction accuracy that can be achieved for the decision values. This may be due to uncertainties in the prediction models. Further, this limit may hold true irrespective of the processing resource applied. In addition, if an accuracy of 100% is achieved then it can be argued that the platforms need not communicate!

8.3 Sensor Trade-off

This section investigates the potential for trade-off between a managed inter-platform communications bandwidth sub-system and sensor employed in a battlespace avionic system.

8.3.1 Investigation Results

The simulation investigation detailed in Section 6.6 generate the process models of Figure 8.3. The system tracking performance is represented in (a) while the identification results are represented in (b).

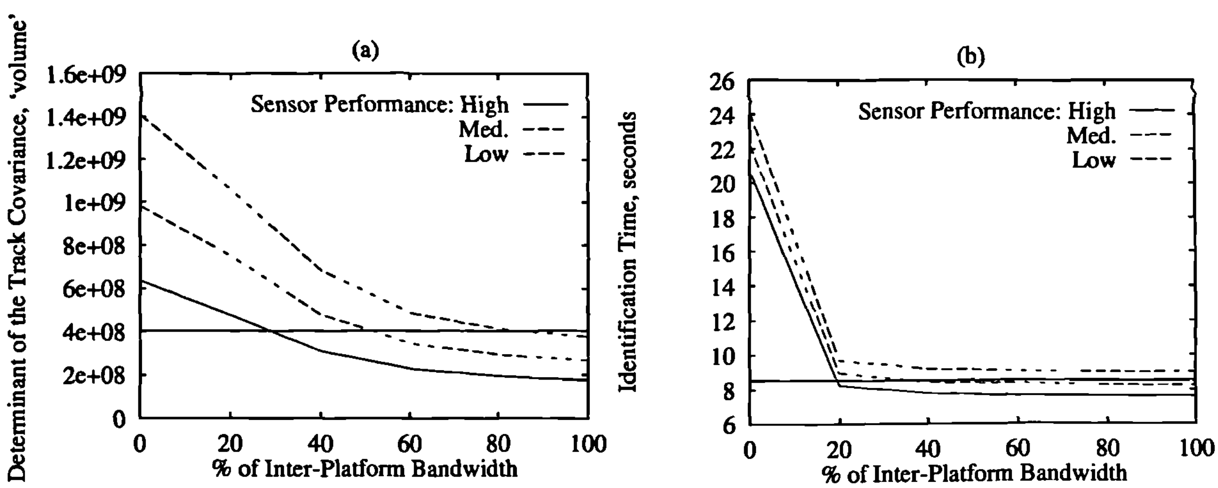


Figure 8.3: Sensor and communications system trade-off potential: (a) tracking and (b) identification performance.

8.3.2 Analysis and Discussion

The results indicate that as the sensor performance is increased the tracking and identification performances also increase.

Here the system results are best for the high performance sensor and worst for the low performance sensor. The medium performance sensor generates results that lie between the low and high performance sensors. Unlike the processor trade-off investigation, an increase in system performance is experienced at the zero and full inter-platform communications as well as at the intermediate bandwidths.

Now the trade-off potential between the sensor and communication system are considered. Firstly the tracking results are considered. Here a customer requires an avionic sensing system with a tracking performance represented by an average covariance of $4e8$ for the scenario described in Section 6.4.4. This requirement is represented on Figure 8.3 (a) by the horizontal line $y = 4e8$. Trade-off potential exist for the customers design. For example, a high performance sensor can be employed at 40% of the full inter-platform bandwidth or a medium performance sensor can be employed at 60% of the full inter-platform bandwidth. Both these options have large error margins, i.e. $> 150\sigma_s$ information based algorithm standard errors.

Similarly, a trade-off potential exists for the identification performance: Consider a customer requiring an identification performance represented by $8.5s$. This is represented on Figure 8.3 (b) by the horizontal line $y = 8.5$. Therefore, this requirement can be achieved by employing a high performance sensor at an inter-platform communications bandwidth of 20% or a medium performance sensor at an inter-platform bandwidth of 80%. Again, these options have large error margins.

These examples show that a trade-off exists between (i) a high performance sensor and low performance communications system, and (ii) a low performance sensor and high performance communications system. The trade-off potentials investigated provide experimental simulation evidence that support the *rejection* of the hypothesis, H5, i.e.

Application Hypothesis H5: Sensor trade-off. 'An information theoretic approach to communications management never provides the potential for trade-off between the communication system and sensor.' **Status: REJECTED** with high confidence.

8.4 Number of Platforms Trade-off

The potential for a trade-off option between the number of platforms and communications system employed in a battlespace avionic sensing system is investigated in this section.

8.4.1 Investigation Results

The simulation investigation detailed in Section 6.6 generate the process models of Figure 8.4. Here tracking performance is represented in (a) with the identification results represented in (b).

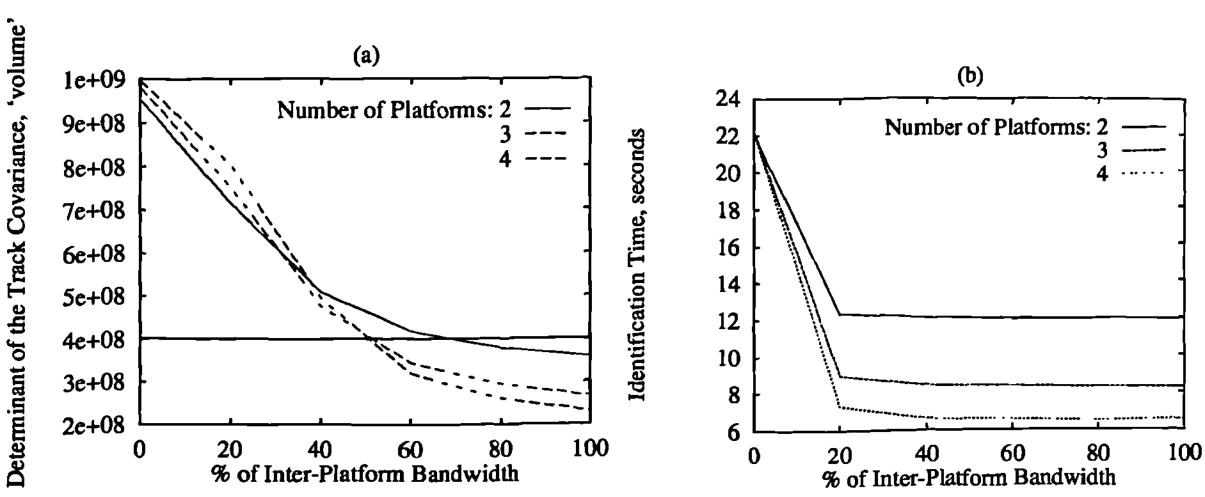


Figure 8.4: Number of platforms and communications system trade-off potential: (a) tracking and (b) identification.

8.4.2 Analysis and Discussion

The results indicate that introducing additional platforms *do not always* improve system performance. This is particularly true for the tracking results. Here at low inter-platform bandwidths the system performance decreases with the addition of platforms. This is due to the fact that the *additional* platform is further away from the targets than the *original* platforms. Therefore, the data introduced to the system is less certain than that generated by the original platforms. Hence, on average the system performance decreases. However, as the inter-platform communications bandwidth increases the data generated by the additional platform reduces the uncertainty of the tracks at the original platforms. This results in improved overall tracking performance.

The identification performance at zero inter-platform communications bandwidth is almost unchanged for different numbers of platforms. However, increasing the communications bandwidth results in relatively large performance differences for increasing numbers of platforms. This improvement in system performance occurs since the identification data, unlike the track data, does not experience temporal degradation in information content.

Now we consider the trade-off potential between the number of platforms and communications bandwidth. The requirement for the tracking results are that the system achieves a performance represented by an uncertainty 'volume' of 4e8. This is represented on Figure 8.4 by the horizontal line $y = 4e8$. Therefore, this requirement can be met by employing three platforms at a communications bandwidth of 60% or two platforms at a bandwidth of 80%. Both these options have large error margins. Therefore, a system trade-off exists. However, the identification results *do not* show a trade-off potential.

The tracking example shows that a trade-off can exist between (i) a large number of platforms and low performance communications system, and (ii) a low number of platforms and high performance communications system. The trade-off potential outlined provides experimental simulation evidence that support the *rejection* of the hypothesis, H6 i.e.

> **Application Hypothesis H6:** Platform number trade-off.
> 'An information theoretic approach to communications management never provides the potential for trade-off between the communication system and number of platforms.'
> **Status: REJECTED** with high confidence.

8.5 Multi-resource Trade-off

This section combines the results generated from investigating the *pair-wise* trade-offs of Sections 8.2 to 8.4. Here the potential of multi-resource trade-offs in decentralised avionic sensing systems is investigated.

8.5.1 Investigation Results

The general way to produce a summary process model for an engineering application is provided in Section 6.6. Here the process models are summarised in graphical form.

Figure 8.5 provides a partial summary of the process models developed during the application investigations of the thesis. This partial implementation ensures brevity and clarity of the summary process model. The graphical representation is built up as follows. From the start point a value representing the 'number of platforms' in the scenario is selected, e.g. 2. For this selection only one type of sensor performance has been investigated, i.e. the medium type sensor. Further, for this branch, the only processor investigated was that which provides 95% accurate decision values. To complete the journey to the leaves of the tree a communications bandwidth has to be selected, e.g. 60%. The track and identification performance of such a system can then be noted. For this graphical representation the average performance values are 4.2e8 and 12 for track and identification respectively.

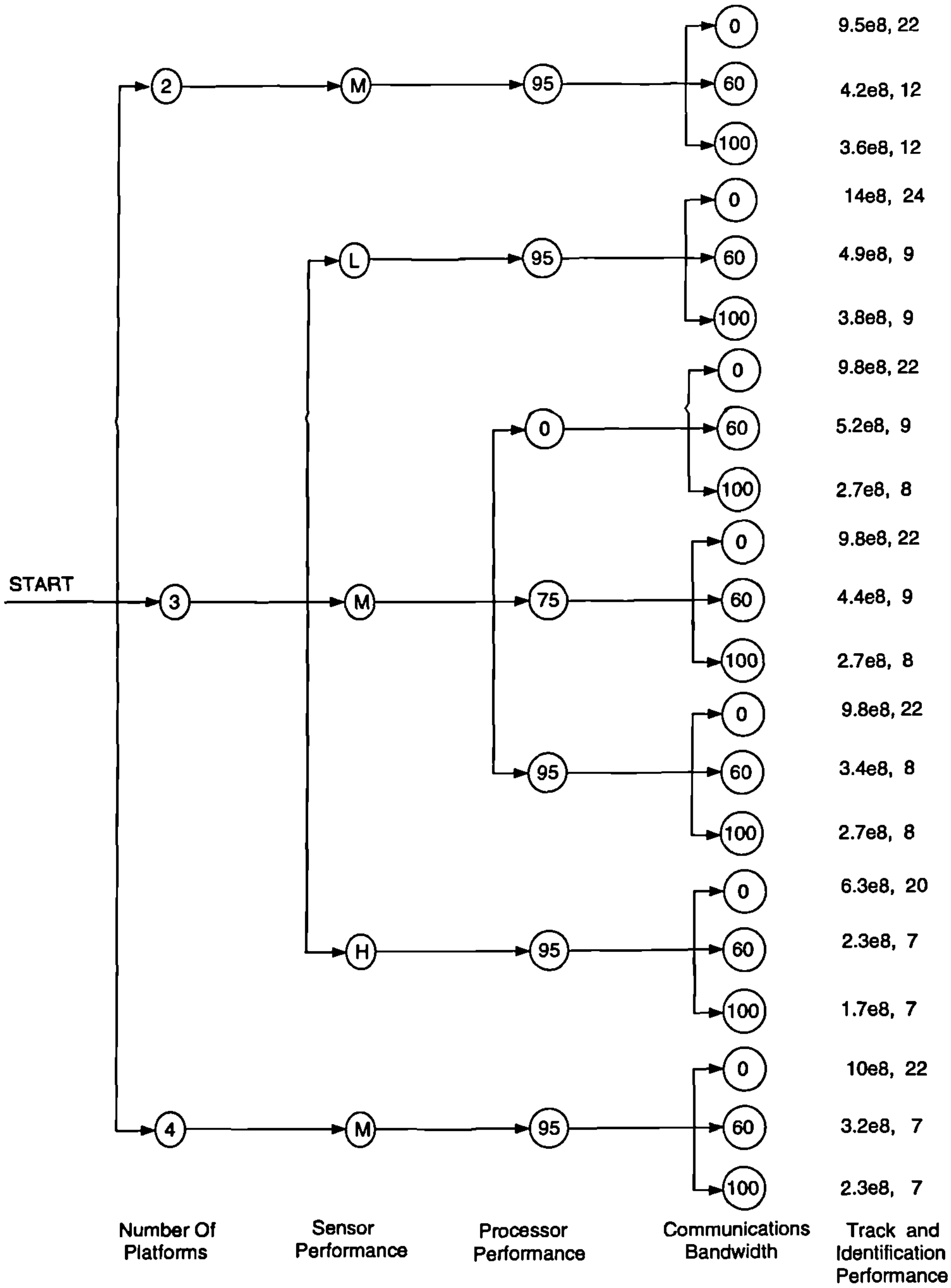


Figure 8.5: Engineering application summary process model.

Design Number	Number Of Platforms	Sensor Performance	Processor Performance	Communications Bandwidth
1	medium (3)	low	high (95%)	high (100%)
2	medium (3)	medium	low (95%)	high (100%)
3	medium (3)	medium	medium (75%)	medium (60%)
4	medium (3)	medium	medium (75%)	high (100%)
5	medium (3)	medium	high (95%)	medium (60%)
6	medium (3)	medium	high (95%)	high (100%)
7	medium (3)	high	high (95%)	medium (60%)
8	medium (3)	high	high (95%)	high (100%)
9	high (4)	high	high (95%)	medium (60%)
10	high (4)	high	high (95%)	high (100%)

Table 8.1: Example decentralised avionic design choices.

8.5.2 Analysis and Discussion

Assume that the customer specifies the system in terms of average track and identification performance, e.g. 4.5e+8 and 9.5 respectively. The leaves of the graphical tree in Figure 8.5 can then be examined to determine those that meet or exceed, i.e. have lower values, than the customers requirement. Working back from these leaves to the root allows the required branches to be determined. All the possible system combinations that achieve the customers requirements are provided in Table 8.1.

It should be noted that labels have been associated with the number of platforms, low = 2, medium = 3 and high = 4; processor performance, low = 0%, medium = 75% and high = 95%; and communications bandwidth low = 0%, medium = 60% and high = 100%. The associated cost weightings for these choices are shown in Table 8.2.

Combining Tables 8.1 and 8.2 gives the overall design choice cost. This is represented in Table 8.3. This indicates that the cheapest design choice is design number 3.

The generation of Table 8.1 in the example provided allows a trade-off choice between the communication system, processor, sensor and number of platforms. As such, the

Level	**Number Of Platforms Cost**	**Sensor Performance Cost**	**Processor Performance Cost**	**Communications Bandwidth Cost**
low	100	25	5	0
medium	200	45	10	30
high	300	100	15	60

Table 8.2: Example component costs.

Design Choice	1	2	3	4	5	6	7	8	9	10
Design Cost	300	310	285	315	290	320	345	375	445	475

Table 8.3: Example overall design costs.

application hypothesis H7 is *rejected*:

> **Application Hypothesis H7:** Multi-resource trade-off.
> 'An information theoretic approach to communications management never provides the potential for trade-off between the processor, sensor, number of platforms and communication system.'
> **Status: REJECTED** with high confidence.

In addition, introducing other engineering constraints, such as fire power, can further refine the selection process. In the example, the individual system chosen was that with the minimum cost.

8.6 Summary and Conclusions

The aim of this chapter was to *test* the thesis application hypotheses H4, H5, H6 and H7 so as to lend support to the proposition:

> **Proposition 2:** Application of Communications Management.
> 'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides the potential for trade-offs to be made/evaluated/calculated between the performance of the communications system and other resources.'
> **Status: MAINTAINED**

This aim has been achieved through the thesis investigations. The results and analysis of these investigations provide empirical evidence that, plausibly, support the *rejection* of all four *application* hypotheses. Further, a number of interesting observations have been noted. These include:

1. **Processor trade-off:** Increasing the performance of the communications management processor, in general, increases the avionic sensing system performance. However, at zero and full communications bandwidth there is no improvement in the system performance.

2. **Sensor trade-off:** Increasing the performance of the sensors employed by the platforms, in general, increases the avionic sensing system performance. This is also true at zero and full communications bandwidth.

3. **Number of Platforms Trade-off:** Increasing the number of platforms in a system *does not always* improve system performance. This is particularly true for the tracking results. Here the change in system performance is dependent on the location of the sensing platform with respect to the targets, the platforms sensor, and its communications system (protocol, bandwidth and management). However, for military avionic sensing systems the other benefits of increasing the number of platforms should also be considered, i.e. increased sensing coverage, increased fire-power and increased redundancy, have to be considered.
   For the identification estimator increasing the numbers of platforms improves the identification time more than that achieved through **1.** or **2.** This situation arises since the identification data is not temporally degraded.

The points lead to the following **'rules of thumb'**:

'Avionic sensing system performance can be improved'

1. *'cheaply' in bandwidth constrained scenarios* by improving the computational resource applied to the communications management.
2. *over all bandwidth scenarios* by improving the sensor performance.
3. *at high bandwidth scenarios* by increasing the number of platforms.

In addition, the method of generating process models that relate system performance to the available resources of an avionic system provides the engineer with responsibility for 'real' *decentralised system design* with an **useful tool** for meeting the customers requirements.

Chapter 9

Conclusions and Future Work

9.1 Introduction

This chapter pulls together the conclusions to the work presented in the dissertation. The primary aim of the chapter is to re-iterate the contribution the dissertation makes to the data fusion body of knowledge. A critique of this contribution is then provided which allows the second aim of the chapter to be achieved, that is, a discussion of future work.

A mapping between the sections of the chapter are provided in Figure 9.1. The remainder of this chapter is organised as follows: Concise details of the contribution the dissertation makes to the data fusion scientific body of knowledge are provided in Section 9.2. A critique of the thesis and lessons learned from the work carried-out are also provided in Section 9.3. Future work relating to the general area of data fusion and specifically to this thesis is described in Sections 9.4 and 9.5 respectively. The application of communications management to other areas is discussed in Section 9.6. Concluding remarks on this chapter are provided in Section 9.7.

9.2 Contribution to Scientific Knowledge

The section provides concise details of the scientific contribution made by the dissertation to the data fusion community. This is covered in four sections, i.e. *development*, *evaluation* and *application* of communications management and related *publications and presentations.*

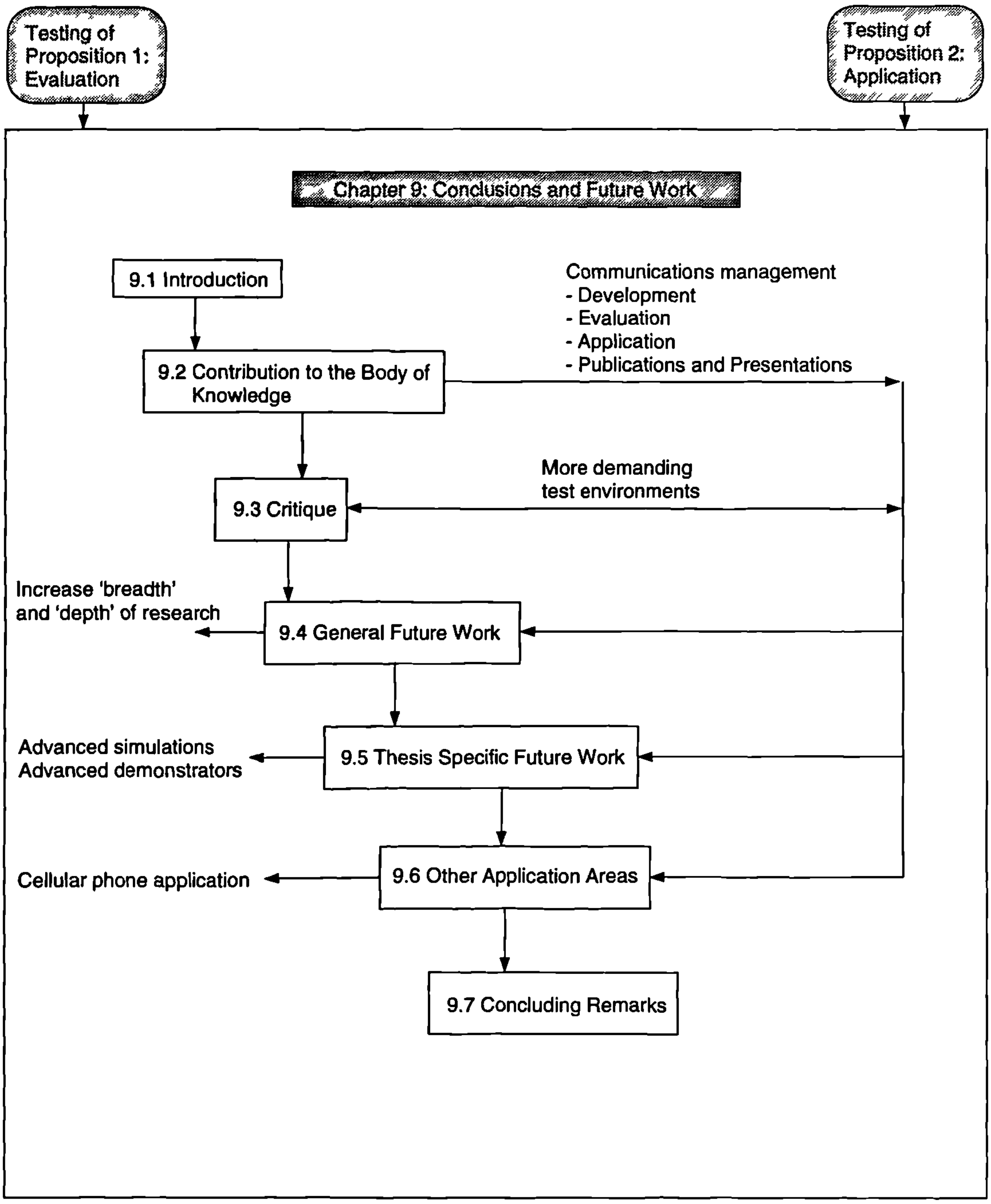


Figure 9.1: Reader's map for Chapter 9.

9.2.1 Communications Management Development

The research carried-out in the development of communications management can be divided into two areas:

(i) A Review of Previous Work

This involved reviewing and applying *minor* developments to work previously carried-out in the general area of data fusion and more specifically in the area of decentralised sensing systems. This resulted in the *minor* scientific contributions of:

1. Identifying the problem area of *dealing with a communications bandwidth constraint in decentralised systems.* This was achieved through a literature review. A summary of this contribution is provided in Chapter 2.

2. Identifying an infrastructure in which communications management could be investigated. This involved a detailed review of algorithms developed for decentralised systems. Further, the application of the channel filter for dealing with a bandwidth limited communication link was analysed. This contribution is documented in Chapter 3.

3. Identifying an information theoretic approach to dealing with bandwidth constraint in decentralised sensing systems. This work employed ideas generated by other researchers for the purpose of sensor management. Further, the concept of *absolute* information as a basis for communications management was identified. This contribution is documented in Chapter 4.

The review of previous work ensured the **originality** of the dissertation.

(ii) The Implementation of Communications Management

This work involved assimilating the knowledge gained from the review and implementing communications management in a decentralised sensing system. This resulted in the following *major* scientific contributions:

1. The development of the *first* information based communications management algorithm for application in decentralised sensing systems. This contribution is documented in Chapter 5.

2. The implementation of the communications management algorithm on a multi-platform multi-target battlespace tracking and identification simulator. This contribution is documented in Chapter 6.

9.2.2 Communications Management Evaluation

The *major* scientific contribution here was concerned with the evaluation of communications management. This investigation formed the first part of the *thesis* and involved:

1. The statement of an *evaluation proposition*, **Proposition 1** (see page 1). This was supported by three hypotheses, H1, H2 and H3, related to the *evaluation proposition*. These are documented in Chapter 5.

2. The *testing* of the evaluation hypotheses by analysis of experimental data from the battlespace simulator.

This demonstrated that an information theoretic approach to communications management out-performed a round-robin algorithm. Further, 'rules of thumb' are provided that indicate when an information theoretic approach to communications management offers benefit over a round robin approach. This ensures that the evaluation proposition is maintained.

This contribution is documented in Chapter 7.

9.2.3 Communications Management Application

The *major* engineering contribution here was concerned with the application of communications management. This investigation formed the final part of the *thesis* and involved:

1. The statement of an *application proposition*, **Proposition 2** (see page 1). This was supported by four hypotheses, H4, H5, H6 and H7, related to the *application proposition*. These are documented in Chapter 5.

2. The *testing* of the application hypotheses by analysis of experimental data from the battlespace simulator.

This demonstrated the trade-off potential between a number of decentralised sensing system resources including communication system, processor, sensor, and number of platforms. Further, 'rules of thumb' are provided indicating how to improve the performance of an avionic sensing system. This ensures that the application proposition is maintained.

This contribution is documented in Chapter 8.

9.2.4 Publications and Presentations

The work reported in the thesis has been published and presented at a number of international conferences, i.e. SPIE, IEEE and NATO(RTO). These papers include:
(Deaves et al. 1996)[1], (Deaves et al. 1997a), (Deaves et al. 1997b), (Deaves et al. 1997c), (Durrant-Whyte et al. 1998), (Deaves et al. 1998).

Further, these papers have been presented at the SRC to managers, engineers, and scientists of BAe and other industrial and academic institutions. The work has been met with a favourable response. Finally, the work was presented as part of a plenary session at the Fusion98 conference held in Las Vegas, July 1998.

9.3 Critique

This section of the thesis provides a critical review of the work carried-out. This review should assist in deciding future work.

The major limits on the thesis derive from the simplifying assumptions made during the work. These include: using simplified sensor models, constant velocity models for the platforms/targets and trackers, using a simplified communications failure model, synchronised sensors and communications modules, simplified data association algorithms, and simplified performance metrics or measures of effectiveness (MOE). However, to hand code such complexities into the models would take a considerable amount of time and engineering resource (Blackman 1986).

Another limit on the work presented is that relatively low numbers of platforms and targets are employed. Again, the coding of realistic trajectories for the platforms and targets requires a considerable effort.

9.4 General Future Work

Possible future work has been divided into two: (i) the general area of data fusion and (ii) decentralised data fusion. It should be noted that although these areas have been sub-divided there is a strong over lap between them.

[1]IEEE peer reviewed paper.

9.4.1 The General Area of Data Fusion

Much work still needs to be done in order for data fusion to be fully accepted into commercial products. The breadth and depth required for this work is of importance for low volume high complexity products employing safety critical systems, e.g. fighter aircraft.

The breadth or 'horizontal' expansion of data fusion will need to encompass all of the areas that to date have received little research effort. These include the theoretical and practical demonstrations of the integration of data fusion, situation/threat assessment and management technologies. This poses the challenge of combining qualitative and quantitative information. The area of human machine interfaces (HMI) also requires investigation. These will be used to present data to a human in a meaningful way. Further, the HMI will be required to input 'intelligent' information from the operator. Another important investigation area is the verification of data fusion systems for flight critical applications.

The depth or 'vertical' expansion of data fusion areas also requires further research. For example, a number of different tracking algorithms have been developed in the data fusion community. These cover a number of different issues including linearity, correlations and multiple hypotheses. However, their performance have yet to be classified in comparison with each other. For this purpose realistic benchmark tests may be required. Recent work in the USA is aimed at providing these benchmark tests (Dempster et al. 1998).

9.4.2 Decentralised Data Fusion

As for general data fusion systems much work still needs to be done before decentralised systems are fully accepted in commercial systems.

An important task will be to verify that the developments achieved for general data fusion systems can be applied to decentralised architectures. This is true for both the vertical and horizontal development areas. Further, the benefits of applying a decentralised paradigm to system design needs to be quantified over the life of a product, i.e. including initial development cost, update cost, and maintenance cost. This should emphasise the benefit of decentralised systems.

The application of decentralised systems may become more popular as the number of commercial centralised sensing systems being developed increases. This will emphasise to the design engineers the problems associated with centralised systems, i.e. flexibility, modularity, scalability and fault tolerance, which may lead them to decentralised implementations. There is an analogy here with the computer industry and the move from centralised mainframes to distributed networks.

9.5 Thesis Specific Future Work

In this section of the thesis possible future work in areas specific to that documented in the dissertation are discussed. This work is sub-divided into two areas: (i) scientific investigations and (ii) more demanding test-bed environments.

9.5.1 Scientific Investigations

The scope of the communications management needs to be broadened in a number of areas including investigations of other communications protocols, i.e. other than the TDMA on which JTIDS is based. These may indicate more suitable communications protocols. For example, an adaptive communications protocol could be developed where more bandwidth was allocated to platforms with more information to communicate. In addition, point-to-point communications protocols need to be investigated as these may provide a more flexible method of allocating bandwidth than a broadcast scheme.

Communications systems with higher and lower bandwidths also need to be investigated. For example, higher bandwidth systems may employ maximum transfers that allow the platforms to communicate all their target information in one sensor update time interval. Here the problem is to adaptively decide the platform communication order. Lower bandwidths may allow communication on only one target from a single platform after a number of sensor update intervals. Here predicting the state of the systems platforms becomes more difficult due to the latency in receiving data.

The performance metrics may have to be developed to capture other characteristics that are of interest to the designer. These include: (i) The engineer may want to have a greater number of design variables. In the work presented in this thesis the performance of constant velocity targets and those that manoeuvre are combined within the same metrics. However, the systems engineer may want to consider these independently. (ii) Limiting the communications bandwidth of a decentralised system may have other system effects, e.g. increasing the number of spurious tracks generated. This leads to other metrics that may be needed by the design engineer.

For the work documented in this thesis the track and identification information values are combined into a target information value by a linear combination. Other methods need to be investigated that may be more representative of the performance the design engineer is looking for. For example, what is the effect of using a combined management strategy where the track and identification values are multiplied together? Further, the linear combination algorithm implemented in the thesis used a constant weighting factor. System performance may be improved by applying an adaptive combination constant.

In addition, the decision philosophy should employ some form of metric that represents the scenario. For example, a single aircraft might place a larger utility on targets close to it than those further away. However, the overall system utility might be equal for all targets. This results in a conflict between the individual and system requirements. A metric to deal with this conflict would then be required.

These investigations have the processor performance represented by the accuracy of the decision values of the communications management algorithm. As mentioned earlier this may be naive. This is an area that requires further research to determine the relationship between the system performance and processor employed to accommodate the communications management.

A simple model of a sensor was employed. Improvements to the system model include employing different variances for range and bearing. Further, the effect that clutter, jet engine modulation and electronic countermeasures the sensor performance have not been investigated (Blackman 1986). These effects should be modelled in future work.

The research did not place much emphasis on the positions of the platforms. Future work in this area includes choosing the optimum positions for the platforms to provide improved track and identification information. This will involve investigations into situation/threat assessment coupled with trajectory management.

Another area that needs investigating is the effect of employing different types of platforms and how these affect the results produced. For example, what is the effect on the system results of employing an AWACS platform with a number of fighter aircraft?

The thesis describes a simplistic hypothetical system design exercise based on track and identification metrics. For real system designs the decision process is very complex. An aid to design choices in military aircraft products include the ALFAS (affordability, lethality, flexibility, availability, and survivability) criteria. Further information on these is provided in (Edwards 1997). Future work will employ these performance metrics.

The prediction algorithms used in the thesis were based on true states degraded by the introduction of random noise. However, prediction algorithms that will work on real systems will be driven by other information sources, i.e. a platforms local view of the scenario. Hence, such predictions will be prone to systematic and random noise influences. How such influences affect the performance of a bandwidth limited decentralised system employing intelligent communications is an area for further research.

The scenarios investigated in the context of the thesis were limited in complexity on a number of issues. These included the relatively low number of sensing platforms employed, the relatively low number of targets used, and low number of states employed for the track and identity estimates. Future work will address increasing the complexity of the scenarios investigated.

The platform topology employed in the scenarios investigated in this thesis were fully connected. However, non-fully connected topologies that employ loops may be used in large networks. This will be an area of future research.

9.5.2 More Demanding Test Environments

In order to further evaluate the effect of communications management in decentralised sensing systems investigations need to be carried-out which employ more demanding test environments. Two possible (enhancing) methods of investigation are currently being considered:

The first method aims to use a sophisticated simulation development environment. Such systems allow complex scenarios to be set-up and used quickly. In addition, pre-coded, vendor supplied data fusion algorithms which carry-out a number of tasks, e.g. missile launch, can be employed.

One such environment is FLAMES (TM) (Flames 1998). This commercial product allows rapid prototyping and system/algorithm evaluation. This system has currently found favour with the USA's DoD. This reduces the problem of compatibility and may increases the number of models, e.g. target and platform, that are publically available. Figures 9.2 and 9.3 represents a graphical output from FLAMES. Here 3-D and 2-D views of the scenario is provided.

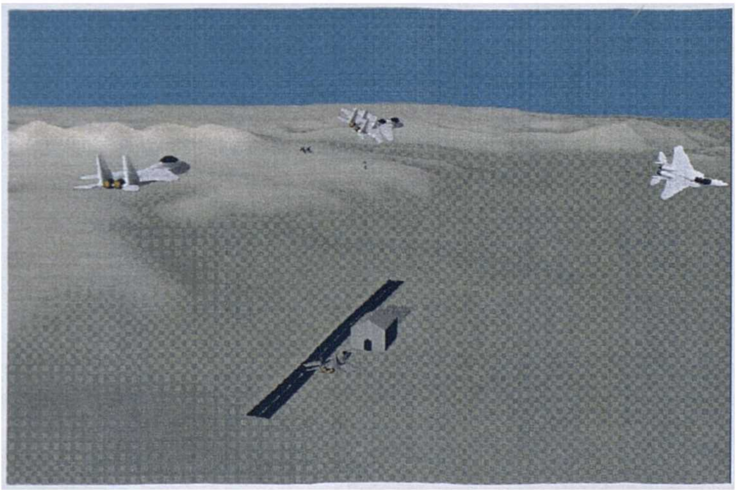


Figure 9.2: The FLAMES development environment, 3-D view.

The second method is to employ a real flight platform to evaluate communications management in decentralised systems. The cost of using real fighter aircraft for such

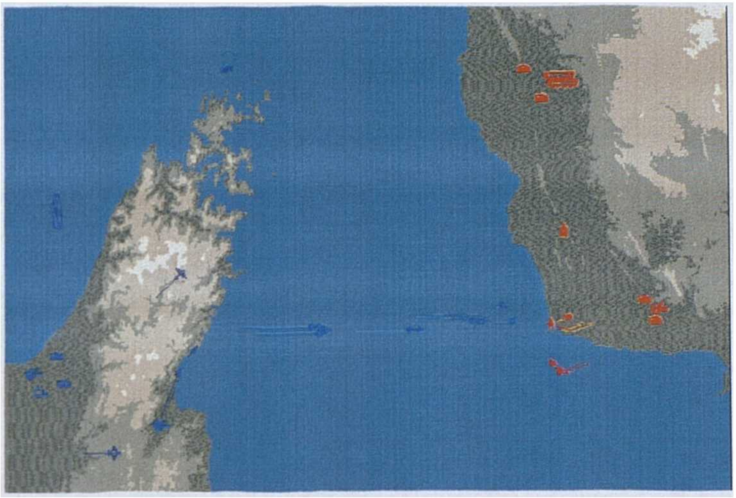


Figure 9.3: The FLAMES development environment, 2-D view.

an evaluation may still be prohibitive. However, research standard flight platforms may be feasible for this task. One such flight platform system that may be suitable is that currently being developed at Sydney University (Wong 1998). Figure 9.4 represents the flight platform. This is a delta design with a wing-span of approximately $2m$.

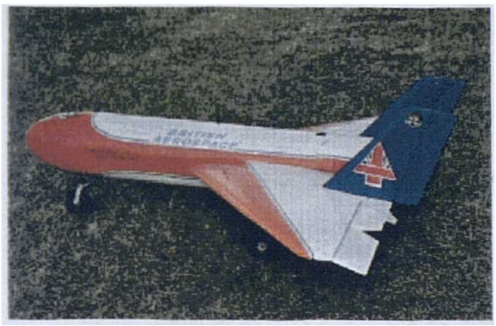


Figure 9.4: The Sydney University flight platform.

9.6 Other Application Areas

In this section suggestions are made of how the knowledge gained from the thesis could be applied to other areas. It should be noted that only brief details are provided here.

9.6.1 Caller Tracking in Cellular Phone Networks

As the number of cellular mobile phone users increases the system communications bandwidth requirements increase in two ways: (i) more overall system talk time is required to satisfy the increasing number of customers, and (ii) the bandwidth required to track customers as they move from one cell to another increases.

Therefore, an intelligent approach to communications management may find application in both these areas. Further, for this example decentralised tracking and identification techniques might find application for customer surveillance in mobile phone networks. This area has recently been reviewed and reported in (Kruijt et al. 1998).

9.7 Concluding Remarks

This short chapter concludes the thesis. Concise details of the contribution of the research documented in the dissertation to the scientific knowledge of data fusion is provided. The two key propositions have been supported by the experimental evidence reported here. They are:

Proposition 1: Evaluation of Communications Management.
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides a measurable increase in performance when compared with ad-hoc approaches.'

Proposition 2: Application of Communications Management.
'An information theoretic approach to communications management, in a bandwidth limited fully connected decentralised sensing system, provides the potential for trade-offs to be made/evaluated/calculated between the performance of the communications system and other resources.'

Hence, since support has been provided for the evaluation and application propositions the overall thesis of the dissertation has been maintained:

an information based approach to communications management in a decentralised sensing systems (i) can out-perform non-information based methods, and (ii) can provide a trade-off potential with other system resources.

Future work would include building on this to (i) develop the communications management algorithm for application in more realistic circumstances, and (ii) build practical systems engineering tools for use in the design of decentralised data fusion and information processing systems.

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